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Bio-Inspired Materials

VOLUME 6

Editors:

Ulisses Targino Bezerra
Heber Sivini Ferreira
Normando Perazzo Barbosa

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Frontiers in Biomaterials

(Volume 6)

(Bio-Inspired Materials)

Edited by

Ulisses Targino Bezerra

*Federal Institute of Paraíba - IFPB,
Civil Construction, Av. Primeiro de Maio, 720,
Jaguaribe, zipcode 58.015-435, João Pessoa-PB, Brazil*

Heber Sivini Ferreira

*Federal University of Paraíba - UFPB,
Department of Engineering and Materials Science City University,
S/N, Castelo Branco, zipcode 58.051-085, João Pessoa-PB, Brazil*

&

Normando Perazzo Barbosa

*Federal University of Paraíba - UFPB,
Department of Civil Engineering City University,
S/N, Castelo Branco, zipcode 58.051-085, João Pessoa-PB, Brazil*

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Email: subscriptions@benthamscience.net



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PREFACE

One of the precursors of the current concepts of “bionics”, “biomimetics”, and “biomimicry” was the Italian, Leonardo da Vinci who, while observing the surrounding world, conceived extraordinary contemplating works and imitation of nature. Two examples are worth noting: the conception of a helicopter from a dragonfly and the design of an ornithopter from the birds and the bat.

The history of science has many examples of the use of materials and/or techniques aiming at certain finality and, after some optimizations and developments, the starting idea is deviated towards further ends, creating innovative products, consequently. This kind of change, all natural, seems to result in the consolidation of the three concepts, cited above. Created from the 50s of the 20th century, these three concepts have caused some misconceptions in the scientific community due to the similarity of their definitions. It can be said that biomimetics is the area of science that studies processes of nature and applies them in everyday problems; bionics is the area of science that studies processes of nature and applies them to technology by means of machines and/or equipment with no concern about the sustainability and/or ethics; while the most recent concept, biomimicry, follows the concept of bionics, ethics and sustainability. The bionics is more objective and focused on immediate results, without concerns with the man-ethics or the nature-sustainability relationships, while the biomimicry is more focused on the respect for nature and its imitation with sustainability (which is improbable to achieve, given the challenge to succeed at an entirely sustainable process). This means that the bionics has a broader scope, immediate and of easy reach, than better biomimicry.

This book covers some aspects of these frontiers of science and is divided into 3 sections:

1. Frontiers in bionics design;
2. Frontiers in bio-inspired construction; and
3. Frontiers in bio-materials.

Each section has some manuscripts that aim at addressing the most recent advances of the desired and expected relationship between human and nature. This relationship also includes political connotations, once the following question is valid: which political regime, form of government or production system would be able to live in harmony with nature?

Section (i) presents the subjects that clarify the direct observation of nature and its use under human aspects, as the case of the construction of surfaces with controlled roughness for applications in high-friction conditions, or the case of textures similar to natural ones, or the observation of the mechanism of mosquito stings and the consequent design of a more efficient drill for medical purposes. Ultimately, it cannot be forgotten that the search for better accommodation/compression of materials and the higher organization/reduction of mechanical stress in structures was made by the humans by extensive observation of nature.

Due to the personal character of the authors and their dedication to research in civil construction, Section (ii) is devoted to all who are dedicated to what can be defined as “artificial construction” of the Earth, in other words, the construction performed by the humans without prioritizing the future. This section addresses the issues on geopolymers (*inorganic polymers*), materials that resemble the structure of soils and natural rocks; procedures that reduce the damage caused by earthquakes in natural construction;

development of superplasticizers from vegetable resins and construction principles using bamboo, as a construction material.

The last section embodies all other subjects not yet covered and takes a look into the future towards the improvement of human living conditions. The goal is to make the human species learn more about nature to live harmonically with it. The life cycle of biomaterials is analyzed, using a new concept of maintenance (here “maintenance” is no longer characterized by periodic interventions performed by humans, but becomes something natural, where maintenance mechanisms are capable of self-regulating, since they are conceived through the biomimetic way).

The structure of this book covers areas of knowledge that have received more contributions from new concepts of bionics, biomimicry, and biomimetics. It is expected to achieve the release of this new world view and further: it is expected that humanity awakes from its lethargy regarding aggressions against nature and starts to think more in the biomimetic way.

Finally, this book is devoted to all the professionals and students who still believe, or have come to believe, that the world can become much better.

Let the burden of the future be light!

Dr. Ulisses Targino Bezerra

Federal Institute of Paraíba - IFPB,
Civil Construction Av. Primeiro de Maio,
720, Jaguaribe, zipcode 58.015-435,
João Pessoa-PB, Brazil
E-mail: dartarios@yahoo.com.br

Dr. Heber Sivini Ferreira

Federal University of Paraíba - UFPB,
Department of Engineering and Materials Science
City University, S/N, Castelo Branco,
zipcode 58.051-085,
João Pessoa-PB, Brazil
E-mail: hebersivini@gmail.com

&

Dr. Normando Perazzo Barbosa

Federal University of Paraíba - UFPB,
Department of Civil Engineering
City University, S/N, Castelo Branco,
zipcode 58.051-085,
João Pessoa-PB, Brazil
E-mail: nperazzob@yahoo.com.br

List of Contributors

Alejandro Manzano-Ramírez	Fraccionamiento Real de Juriquilla, CINVESTAV-Querétaro, Libramiento Norponiente # 2000, Querétaro, Qro, México
Ana Cecilia Vieira Nóbrega	Department of Civil Engineering, Federal University of Pernambuco, Recife-PE, Brazil
Benedikt Demmert	Department of Materials Science and Engineering, Institute of Glass and Ceramics (WW3), Friedrich-Alexander-University Erlangen-Nuremberg, Martensstrasse 5, Erlangen, Germany
Corinna F. Böhm	Department of Materials Science and Engineering, Institute of Glass and Ceramics (WW3), Friedrich-Alexander-University Erlangen-Nuremberg, Martensstrasse 5, Erlangen, Germany
Eng. Kai Li	College of Civil Engineering, Hunan University, Hunan Sheng, China
Eng. Piet Stroeven	Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands
George Rzevski	Centre for Complexity and Design, The Open University, Milton Keynes, UK
José Augusto Gomes Neto	Federal University of Paraíba, João Pessoa-PB, Brazil
José Luis Reyes Araiza	C. U. Cerro de las Campanas, Centro, DIPFI, Facultad de Ingeniería, Universidad Autónoma de Querétaro,, Querétaro, Qro, México
Khosrow Ghavami	Pontifical Catholic University of Rio de Janeiro, Rio de Janeiro, Brazil
Mario Villalón	Av. Playa Pie de la Cuesta, No. 702, Desarrollo San Pablo, Centro de Ingeniería y Desarrollo Industrial (CIDESI), Santiago de Querétaro, Qro, México
Marios C. Phocas	Department of Architecture, University of Cyprus, Nicosia, Cyprus
Martina Schüßler	Department of Materials Science and Engineering, Institute of Glass and Ceramics (WW3), Friedrich-Alexander-University Erlangen-Nuremberg, Martensstrasse 5, Erlangen, Germany
Niki I. Georgiou	Department of Architecture, University of Cyprus, Nicosia, Cyprus
Normando Perazzo Barbosa	Dept. of Civil Engineering, Federal University of Pernambuco, João Pessoa, Brazil
Odysseas Kontovourkis	Department of Architecture, University of Cyprus, Nicosia, Cyprus
Sandra Reyes Ortiz	Federal University of Paraíba, João Pessoa-PB, Brazil
Stephan E. Wolf	Department of Materials Science and Engineering, Institute of Glass and Ceramics (WW3), Friedrich-Alexander-University Erlangen-Nuremberg, Martensstrasse 5, Erlangen, Germany Friedrich-Alexander University Erlangen-Nürnberg (FAU), Haberstrasse 9a, Interdisciplinary Center for Functional Particle Systems (FPS), Erlangen, Germany
Theófilo Barreto Moreira Oliveira	Federal University of Paraíba, Campus Mamanguape, Brazil

Ulisses Targino Bezerra	Federal Institute of Paraíba-IFPB, Civil Construction, Av. Primeiro de Maio, 720, Jaguaribe, zipcode 58., João Pessoa, Brazil
Viktor Stabnikov	National University of Food Technologies, Kyiv, Ukraine
Volodymyr Ivanov	National University of Food Technologies, Kyiv, Ukraine

CHAPTER 1**Bio-Pulse Oscillations Driven Design of Kinetic Structures****Marios C. Phocas*, Odysseas Kontovourkis and Niki I. Georgiou***Department of Architecture, University of Cyprus, Nicosia, Cyprus*

Abstract: Natural organisms consist of an integral, multi-layered, finely tuned and differentiated combination of basic components and may act as role models in providing kinematic principles to structures subjected to time-varying external conditions. The term biomimetic design is introduced in the present chapter to refer to the synthetic integration of nature mechanisms considered in the development and composition of kinetic structures. Respective kinematic principles transferred in the design of structures follow performance-based open-loop design processes, made possible through interdisciplinary modes of operation in research and design. Following initial visions of kinetic architecture in achieving structural flexibility and adaptability, respective prototype developments, achieved until recently, follow a hard-mechanical approach that enables the development of deployable and transformable actuated bar structures. Confronted with implicated geometrical limitations, the mechanical complexity and high energy consumption of such systems, a design approach derived from soft mechanics is hereby proposed. So far, few realizations of bending-active elements and hybrid systems with enhanced reversible elastic deformability are based on plant movement principles. Following an overview of related form-finding simulation and analysis methods, further bio-pulse oscillation processes, present in nature, are proposed to extend the biomimetic design spectrum. In a case example, motion principles of jellyfish pulse oscillations have been transferred, scaled-up, and integrated into the design of a high-rise structure.

Keywords: Biomimetic Design, Kinetic Structures, Soft-Mechanical Approach, Bio-Pulse Oscillations, High-Rise Structures.

1. INTRODUCTION

The basis for a physically dynamic architecture that is supported by improved understanding of biological systems, and scale in particular, has been increasingly investigated in recent years. In this respect, three main development directions may be identified [1]: Biomimetics functional morphology (form and function),

* **Corresponding author Marios C. Phocas:** Department of Architecture, University of Cyprus, Kallipoleos St. 75, 1678 Nicosia, Cyprus, Tel: +357 22892969; Fax: +357 22895056; E-mails: mcphocas@ucy.ac.cy

biocybernetics, and sensor technology, and robotics and nanobiomimetics. The term ‘biomimetics’ implies adaptation or derivation from biology, embracing the practical use of mechanisms and functions of biological science in architecture and engineering. Research on biomimetics seeks to contribute to the development of operational, effective and energy efficient systems as to varying functional needs and external conditions. In particular, biomimetic design seeks to integrate aspects of nature’s role model mechanisms into the development and design of structures, through performance-based approaches [2]. An important aspect is the effective exchange of research between the disciplines on a methodological level. In this respect, knowledge gained from biological paradigms and processes in biomechanics and functional morphology, through analysis and evaluation, needs to be understood and abstracted in its principles. The derived technology is then implemented through prototyping and testing. Respective nonlinear design developments enable integration supported by technology transfer of related technical aspects to serve, on one side, the holistic design approach and open-loop research-based interdisciplinary design processes, experimentation and advances on the other. Results obtained aim at an architecture able to homogenize the discipline areas concerned, in technical terms for example, those of materiality, structure and form [3].

Advances in embedded computation, material design and kinetics on the technological side, and increasing concerns about sustainability, social and urban changes on the cultural side, provide a background for emerging kinetic architectural solutions, based on initial visions proposed in 1970 by Zuk and Clark for a ‘Kinetic Architecture’ [4]. The exploration of kinematics and responsiveness in architecture relies on changing the properties of structures and materials, in order to create reconfigurations or real transformations of surfaces and systems. Kronenburg argues that for a building to be ‘flexible’, it must be capable of adapting, as a way to better respond to various functions, uses and requirements, transformation, defined as alterations of the shape, volume, form, or appearance, movability and interaction, which applies to both the inside and outside of a building [5]. Engineering precedents, for the development of kinetic structures, include commonly known systems, such as deployable tensegrity and scissor-like systems [6]. These precedents form an important part of the practical knowledge currently available for the development of shape control within our architecture. Nevertheless, in the majority of examples developed and implemented so far, the resultant system reconfigurations are limited between a ‘closed’ and an ‘open’ state, or realized through integration of ‘locking’ techniques and rigid body mechanisms. In cases where real transformability is aimed at, the systems rely on embedded computation and mechanical actuators [7]. Such mechanisms often lead to an energy inefficient and complex kinetic behavior [8].

Flexible motion principles have, thus far, been transferred to architecture following plant movement principles that have been scaled-up and integrated into lighter and less complex bio-inspired kinetic elements. In particular, global flexibility is often achieved through the versatile behavior of locally differentiated regions with special morphological features that act as living hinges and allow for large elastic deformations [9]. In this frame, elastically deformable members may act as primary components in hybrid structures with enhanced capabilities in their kinematics. Planar bending-active members of relatively thin section for instance, prompt controllable elastic deformations, while they preserve geometrical reversibility, thus achieving different configuration transitions [10]. The embedded energy, stored inside the material's molecular structure, allows bending-active members to compose autonomous kinetic mechanisms, able to undergo geometrical deformation without the empowerment of additional energy. The deformation process can increase the member's stiffness and establish sufficient global stabilisation of the system. This behavior offers potential new forms of flexibility, adaptability and deformation using the memory effect in structural members [11].

Kinetic structures in general, and the complexity of material-inherent behavior more specifically, necessitate a coordinated series of design, exploration and analysis. In this way, early design investigations are further informed and supplemented with full mechanical descriptions [12]. Complexity is innate; a repercussion of the inextricable relations between material, structural capacity and form. Nevertheless, within each mode of design, the complexity needs to be decoded into manageable components, determining the variable and invariable properties. To do so, each mode of design can be addressed *via* the distinct definitions of topology, force and materiality. Such definitions establish the character of the system, where integration generates behavior. In this frame, simulation approaches of force-density, dynamic relaxation methods and finite-element analysis (FEA) will be explained in providing a holistic methodology of preliminary topological investigation and detail load-deformation analysis, respectively.

Following this state-of-the-art analysis, the soft-mechanical approach may include aspects of elastic and fluid dynamics, as suggested with respective examples of biological processes of bio-pulse oscillation mechanisms existent in nature. Such mechanisms extend from the human heartbeat for blood circulation, over fluid drops in motion, to the jellyfish motion behavior, and are briefly presented in the chapter. A biomimetic design example, developed at a conceptual level, has been derived from the jellyfish motion principles and is presented in the last section of the chapter. The example refers to the design, simulation and analysis of a high-rise hybrid structure of 250 m height and 25 m diameter [13]. The structure

consists of an innovative lightweight load-bearing system and incorporates a kinetic core mechanism that provides through vertical airflow, improvement of the environmental conditions of the building spaces and the surrounding urban areas of high density. The kinetic structure is envisioned to operate as an urban ventilation chimney for air polluted cities and contribute to microclimate improvements.

2. BIOMIMETIC DESIGN

Biomimetics, also synonymous with ‘biomimesis’, ‘biomimicry’, ‘bionics’, ‘biognosis’, ‘biologically inspired design’ *etc.* implies copying or adapting or deriving from biology [14]. Recently, a definition of biomimetics has been developed [15]: ‘interdisciplinary cooperation of biology and technology or other fields of innovation with the goal of solving practical problems through the abstraction, transfer, and application of knowledge gained from biological systems’. Although this definition primarily highlights the fundamental steps in knowledge transfer, at the same time, the investigation of natural structures provides clarification of their respective function, which may be a result of related forms, processes and interactions [16]. The term biomimetic design is then, used to characterize the transfer of structural mechanisms and construction processes in architecture based on principles of biological systems behavior and their technological interpretation. This definition should also include the application of mechanisms from nature in the design of structures in architecture. In this respect, the process of biomimetic design consists of three stages: research, abstraction and application.

Biomimetic design offers a promising perspective within the field of architecture, requiring an instrumental and rigorous approach to the supporting and driving modes of the design process. In this sense, biomimetic design also requires an overarching theoretical framework to ground any relevant observation, experimentation, transfer and application and to give it a direction in relation to the production of kinetic structures, in terms of a performative architecture. Relevant research constitutes a specific field of growing complexity and can be successfully pursued only if it is based on certain discipline interrelations [17]. In this frame, interdisciplinarity, *i.e.* a group of related disciplines having a set of common purposes, coordinated from a higher purposive level, gains significance throughout the development process. In parallel, digital platforms of operation may support interdisciplinary design processes on the basis of the latest advancements through the introduction of computing facilities, simulations and numerical methods of analysis [18]. Digital design enables designers to collaborate with other disciplines from outside fields, visualize, research and modify structure and system performance with relatively high accuracy. At the

same time, this mode of operation requires designers to rethink alternative strategies, in order to establish a robust connective link between disciplines and specializations.

In particular, biomimetics, and by extension biomimetic design, may be developed on a vertical scale. The approach followed by a biology push consists of a first step on carrying out basic biological research in biomechanics and functional morphology. As a second step, new insights are prepared for, and made available to, technology for further processing, *i.e.* bottom-up approach. Additionally, an alternative strategy may be followed by a technology pull, through the investigation of possible biological model solutions for specific technical problems, *i.e.* top-down approach. The latter approach enables the development of bionically inspired products in shorter time, whereas the former approach has the potential to yield higher innovation [19]. Furthermore, a stochastic investigation utilizes large databases of phenomena from nature, to systematically access information delivered by life sciences for questions arising in technological disciplines. The European Space Agency for example, uses a biomimetics database to look for suitable role models from nature. The ordering system for the database is the ‘technology tree’, ordering natural role models in the fields of structures and materials, mechanisms and processes, behavior and control, sensors and communication and generational biomimicry. Still, such collection of data does not directly aim at a technology transfer in architecture. Instead, the interdisciplinary design team is responsible for the evaluation of alternatives and the application of principles in the design process. In respect to the architectural design, a clear linear development of a biomimetic design is often difficult to maintain, since the design and development of solutions in architecture follow a rather nonlinear combination of rational and subjective aspects, which underlie, among others, various social, morphological, aesthetic and technical criteria. Nature role models may connect at different stages of the design process, whereas the latter often contains unidirectional orientation. In this way, biomimetic design may even constitute a creative transformative process.

3. KINEMATICS

The necessity for an architecture that is not static but instead, has the ability to adapt to time changes through systems with embedded kinetic mechanisms was initially proposed [4], while active control concepts envisioned, were directly influenced by respective advances in aerospace and mechanical engineering [20]. In particular, concepts for structural deformation control have been proposed, such as the ‘variable controlled deformation’ method, through the application of stressing tendons within the structure. The control members should be capable of being variably and automatically tensioned to counteract excessive deformations.

Such a control mechanism was conceptually applied in five classes: axial, flexural, torsional, instability and vibration and seismic control. Along these lines, the human body may be considered as the most representative example of a dynamically interactive living organism. The engineer Guy Nordenson describes the phenomenon in active kinetic systems as creating a building like a body: a system of bones and muscles and tendons and a brain that knows how to respond [21]. Thus, the structural mechanism, responsible for different geometrical configurations of the lightweight components through folding, sliding, expanding and transforming in size and shape, among others, and the control system, which directs the structure towards specified transformations, are significant for the kinetic operability of the system. In the so-called hard-mechanical approach, the geometry of the members, the connections' typology and the boundary conditions comprise critical parameters. They define the kinematics and therefore the transformational possibilities of the system [22].

Kinetic systems have mainly been studied in terms of deployable structures [23]. Tensegrity structures, *i.e.* self-stressed systems composed of tension and compression members [24], may be transformed from a closed configuration to a predetermined expanded form, in which they are stable and can carry loads [25] by altering the compression or tension of members' length [26, 27]. Planar and spatial scissor-hinge elements comprise further common types of deployable structures, able to expand horizontally or in both, horizontal and vertical direction [28 - 30]. While such structural elements need additional stabilizing members, like cables or other locking devices, self-stable structures can be achieved by applying special geometrical configurations through additional inner scissor-like-elements [31 - 34].

Structural systems, bearing the aforementioned deployable characteristics, have been industrialized but face some particular challenges which do not easily align with the fundamental construction principles normally used in machine design. The hard-mechanical approach prioritizes uniformity, regularity and compatibility over individuality and adaptability. As a result, mechanical devices are usually conceptualized as mono-functional and standardized modules, whose mechanics conform to a grid of orthogonal axes. A mechanical system like this, however, entails many limitations and is difficult to be applied in other than planar and parallel configurations. Here, adaptation can only be achieved at the expense of additional mechanical complexity, which results in heavy and maintenance-intensive structures [35]. An example of a spatially transformable kinetic tensegrity structure is the 'Kinetic Tower' [36]. The particular structure forms a realization of the flexible guyed mast vision of Frei Otto [37]. The outrigger system of rhomboid-shaped core units and vertical interconnecting cables provides different spatial bending shapes through integrated dampers on the

joints. Related developments, aiming for real form flexibility, identify design strategies of replacing main structural components with actuators. Consequently, depending on the actuators number used and their specific characteristics, the structures' overall weight and the energy consumption for their kinematic reconfigurations are disadvantageously affected [8].

3.1. Soft-mechanical Approach

Biology is of particular interest, since it provides not only isolated phenomena in the design of structures, but also new technical and methodological strategies. An important characteristic of natural systems is the integral, multi-layered, finely tuned and differentiated combination of basic components that lead to structures with multiple networked functions [38]. Natural structures consist of only a few basic components that are geometrically, physically and chemically differentiated. Softness and body compliance are significant features, often exploited by biological systems, which tend to seek simplicity and show reduced complexity in the interactions with their environment [39]. Consequently, in contrast to the hard-mechanical approach followed thus far by the construction industry, soft-mechanical principles, conceptually derived from the study of natural systems behavior patterns, have shown their potential in succeeding a vast diversity of morphological adaptation, allowing, at the same time, a promising outcome in terms of energy performance, stability, material minimization and aesthetics.

Compared to technical systems, flexible structures in nature replace local hinges by elastic deformations and thus, distribute the acting forces over a wider area where bending takes place. Force is not directly translated into kinetic motion and displacement; instead, it is stored temporarily into the material's molecular structure, *i.e.* residual force, allowing an incremental distortion of the material. Following this principle, bending-active members carry the imposed loads visually and therefore, reflect directly their load-deformation behavior. During deformation, the residual forces, caused by active bending, increase the residual stresses of the structure and therefore, enable it to be self-stiffening [11]. Within this frame, planar surfaces can form single, or double, curvature surfaces according to the type and magnitude of the force applied.

In elastic structures, rigidity can be increased either by the combination of bending and tension prestress stored within the individual members, or by coupling multiple elements to a hybrid system. In principle, hybrid systems are defined through linkage of different components in parallel and/or in series that are combined to resist forces by developing a specific mechanical behavior due to their different resisting nature [40]. The potential of hybrid systems lies on the synergetic possibilities emanating from exploiting the system disparities:

reciprocal compensation of critical stresses, system-transgressing multiple functions of individual components and increase in rigidity through opposite systems deflection [41]. The use of bending principles in hybrid systems enables not only initial complex geometries, and their subsequent stabilization through additional prestress, but also the capability of the members to undergo reversible deformations [42].

Elastic kinematics, as found in complex plant movements, has already acted as role model for the development of new bio-inspired adaptive systems. Out of the broad spectrum of biomimetic products, fiber-reinforced composites represent some of the most successful biomimetic technical applications. The potential of developing fiber-reinforced compound materials is very high because the fiber-matrix structure in plants is comparable to those in technical materials and the complex fiber-matrix structures in plants are organized in at least five hierarchical levels [43, 44], from the molecular scale over to the nanoscale and microscale to the macroscale [45].

Despite not following directly the abstraction of a plant movement, two recent architectural examples of a building envelope design with kinetic elements were inspired and derived from the observation and analysis of natural role models. The first example is the development of the shading system of the biomimetic media façade of the Thematic Pavilion at Expo 2012 in Yeosu, South Korea, which was strongly influenced by the prototype *Flectofin*, derived, in turn, from the biomimetic principle of the valvular pollination mechanism in the *Strelitzia reginae* flowers [35, 46]. In principle, the backbone element of the flower is made of a flat section that is attached perpendicularly to the fin; a thin shell element. The sideways bending of the fin is a failure mode initiated by torsional buckling, when bending of the backbone develops. Consequently, a recurved surface is formed in the fin, which provides the entire system higher stiffness [47]. Following this kinematics principle, the facade elements are made of slightly curved plates of glass-fiber reinforced polymers, supported by two hinged corners at the top and bottom. In the other two corners, a small compressive force is applied by an actuator in the plane of the lamella, which leads to a controlled buckling. Thus, the structural effect, responsible for the members' kinematics, is initiated by lateral torsional buckling and continues in a non-symmetrical bending mode. The second example is the *SoftHouse Project's* adaptive façade. The development originated from a kinematics investigation in stripe-like configurations to conclude to a highly adjustable, multifunctional adaptive skin. The stripes' membrane covering consists of both glass-fiber mesh and elastic tensile material depending on the elongation tolerance in each case individually. The façade components provide three kinds of actuating force; linear actuating, responsible for swivelling the element at mid-span locations; rotating actuating supports to

form twisting reactions and; sliding roof-end supports to execute bending deformations [48].

Technically, the use of bending principles in hybrid systems enables initial complex geometries, subsequent stabilization through additional pretension, reversible deformability and sustainable controlled kinematics of the members. The flexible guyed mast model, originally proposed by Frei Otto [36], consists of a central flexible curved element that may obtain different configurations through three sets of longitudinal cables, and provides such an adaptive hybrid bending-active system. Another example is the hybrid prototype structure of three polyethylene terephthalate glycol, PETG lamellas interconnected by struts of variable length [49]. Further developments of adaptive hybrid structures, consisting of primary bending-active members and a secondary system of struts and cables with closed circuit and variable length, have been proposed in [11, 50, 51]. In these prototype developments, the cables have a dual function: to stabilize the primary members and to provide the structure with controlled transformability, in order to obtain different configuration states throughout its kinematics.

3.2. Simulation Approaches

The design development and simulation of the physical behavior of complex kinetic structures based on soft-mechanical principles, including the implementation of form-finding techniques, were traditionally achieved using physical models; a well-known direction of investigation pioneered in the work of Antoni Gaudi and Frei Otto [52]. Although, the experimental form-finding allowed the visualization of results, two main disadvantages have been discussed in [53]; namely, the limited number of variants and the measurement of physical models. In addition, conventional model-making and analysis might lead, in most cases, to time consuming and geometrical inaccuracies during the investigation, and to results that prevent the establishment of feasible modelling and simulation procedures. On the contrary, recent advances in computational design and simulation open up new directions of research, providing a methodological shift towards more effective implementation of tools and mechanisms, enabling their involvement in various stages of the process, from the conceptual design, to the simulation of their physical behavior, and then to the analysis of structural capacities. The aim is precisely to capture their behavior and achieve an active integration between geometrical development and physics-based simulation of modules and systems, as well as an efficient numerical analysis of the results.

In the first case, the preliminary typological investigation of morphologies and the load-deformation analysis of systems are examined. In examples of conventional

kinetic systems, the implementation of computer simulation, as mechanism for visualization of motion behavior, is required using advanced 3D modelling tools with animation and rendering capabilities [54]. In this category, the simulation approaches might be established around the idea that complex morphologies can be decoded into manageable components in the rationale of a bottom-up procedure [55]. Once the shape and motion behavior of each unit are determined, by synthesizing mass customized structural elements together, the overall morphology of the system can be achieved [56]. The application of parametric design and control approaches enables the visualization of the design solutions, close to the actual animation of their motion behavior; an implementation that can be found either in conceptual or detailed design stages.

Tensegrity, tensile and bending-active systems necessitate more sophisticated techniques than previous approaches, aiming not only at their visual animation, but also their digital form-finding. Such mathematical approaches derive from force-density [53] and dynamic relaxation methods [56, 57]. The force-density method describes the equilibrium state of any general network structure composed of nodes and edges under suspension or stretch between given fixed points [53]. The method is based on the force-length ratio or force-density that is applied in every single structural element. The loading in each element prompts the lengthening and deformation of the overall structural system. The process continues until the sum of all forces in each node is zero, leading to an equilibrium state of the system [58]. The dynamic relaxation approach is another form-finding technique, aiming at the geometrical definition of network structures consisting of nodes and cables. According to [57], the method aims at gradually finding the motion of each structural node until it reaches a static equilibrium state. Through an iterative process, the system comes to rest under the influence of a ‘damping’ behavior that reflects the time-based simulation of a pseudo-dynamic process, following viscous damping principles [59].

Recently, computational methods in the area of form-finding concentrate on simplifying procedures, opening new directions in the development of tools that can be widely used in other disciplines, like in architecture, for the geometrical development of structures. The intention is to implement such tools in the early stage of the design process, while experimental investigations are taking place, incorporating material and loading characteristics of structural systems. A well-known computational approach is the particle-spring technique on the basis of Hooke’s Law of elastic stress-strain behavior [60, 61], which may be applied to capture the optimum shape of both hard and soft-mechanical systems. Specifically, this method involves a structure that is translated into a network of particles and springs that represent nodes and edges, respectively. The springs are assigned according to their stiffness and damping properties and the particles are

influenced by gravity and self-loading conditions. During the form-finding process, the loads cause the displacement of the particles and hence, the deformation of the overall system. The springs oscillate until their velocity is minimized, resulting in an equilibrium position of the geometry under investigation [62]. Among others, examples of particle-spring tools include the CADenary [63], the Spring FORM software [64] and the parametrically controlled physics-based engine Kangaroo (plug-in for Grasshopper) [65]. The latter assigns a spring force behavior based on the length of springs, which is defined by ‘start’ and ‘rest’ length values; a metric control approach that, in turn, influences the tension behavior of the linear structural members.

The methods described above primarily support a geometry-based design approach of kinetic systems, within the preliminary design stage. The system’s geometry is predefined based on analytical geometry or experimental form-finding methods, both of which are used as a controlled means to approximate the actual form-finding. Material limitations are considered analytically. Furthermore, in numerical form-finding through FEA, full control of the material behavior-based geometry is enabled. Material characteristics and limitations are included in the numerical analysis model. In particular, form-finding techniques in bending-active members based on FEA are presented [62]. FEA proves to be a valid form-finding calculation method [66], and takes into account both material and geometrical nonlinearities that occur during the members’ large deformations and displacements.

Furthermore, the conventional form-finding methodology of coupled bending-active structures examined [67], points to the need for all stresses developed in each deformation step to be accordingly stored inside the updated geometry coordinates of the model before calculating the next step. For the erection, and step-wise deformation activation of bending-active elements, Lienhard suggests the so-called elastic cable approach [68]. Contracting cable elements are used to pull together nodes from both individual members until they reach the required deformed configuration. The cable elements are assigned to constant pretension and their elastic stiffness is regulated to a lower level for each static analysis that follows. This process enables cable components to shrink in length and the two end-assigned nodes of the structural members to join. For the form-finding of coupled bending-active members, this technique allows complete freedom of the equilibrium paths followed during the deformation process.

4. BIO-PULSE OSCILLATIONS

It is well acknowledged that dynamic structural forms derived from nature, as well as their relation to the mechanics of moving fluids, can lead to highly

effective kinematics [69]. The design of organisms responding to drag, flow and lift offers kinetic efficiency on one hand, while physical adaptations observed in natural forms offer solutions for form-flexible architecture that exists in changing environments, on the other.

The motion strategy derived through pulse oscillations resembles, for example, the process of pumping blood through the body (Fig. 1) [70]. The heart acts like a four-chamber pump, with two atria and two ventricles. De-oxygenated blood returns to the right side of the heart *via* the venous circulation. It is pumped into the right ventricle and then to the lungs, where carbon dioxide is released and oxygen is absorbed. The oxygenated blood then travels back to the left side of the heart into the left atria, then into the left ventricle from where it is pumped into the aorta and arterial circulation. The pressure created in the arteries by the contraction of the left ventricle is the systolic blood pressure. Once the left ventricle has fully contracted, it begins to relax and refill with blood from the left atria. The pressure in the arteries falls while the ventricle refills. Through this process, it achieves diastolic blood pressure. In doing so, the human heart is able to create its own electrical impulses and control the route the impulses take *via* a specialized conduction pathway.

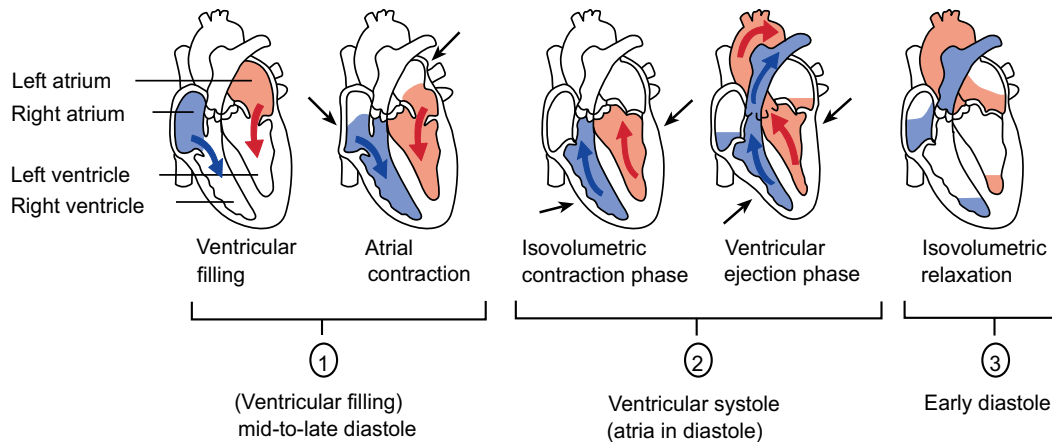


Fig. (1). Principle of blood circulation through human cardiac operation.

In terms of natural form transformation during pulse-oscillations, first insights may be obtained from fluid drops in motion. The governing principles are derived from the law of vortex-motion in a perfect fluid, when there is movement of one body of fluid within another and the resulting phenomena of friction at the surfaces between [71]. When a drop of water, for instance, is gently released at the bottom of a glass of water, its momentum makes it rise slightly above the surrounding water and, by doing so, it communicates motion to the water around it.

The rising drop thrusts its way through, like a solid body and it tends to drag the surrounding water after it, through fluid friction. These two motions combined give rise to vorticoid configurations. Under higher and more continuous pressure, the form of the vortex is modified and may be further modified by slight adjustments of temperature or by interrupting the rate of flow. The descending drop turns into a complete vortex-ring: it expands and attenuates its waves about, and the descending loops again turn into incipient vortices. In either case of the speed of the descending drop in another liquid, the result is closely analogous to that of a medusa or jellyfish with its bell or 'umbrella' and its clapper or 'manubrium' (Fig. 2). The variability of the results obtained, with regard to the motion pattern of fluid drops in motion, verify the way certain simple organic forms might be naturally assumed by one fluid mass within another, influenced by gravity, surface tension and fluid friction, under balanced conditions of temperature, density and chemical composition.

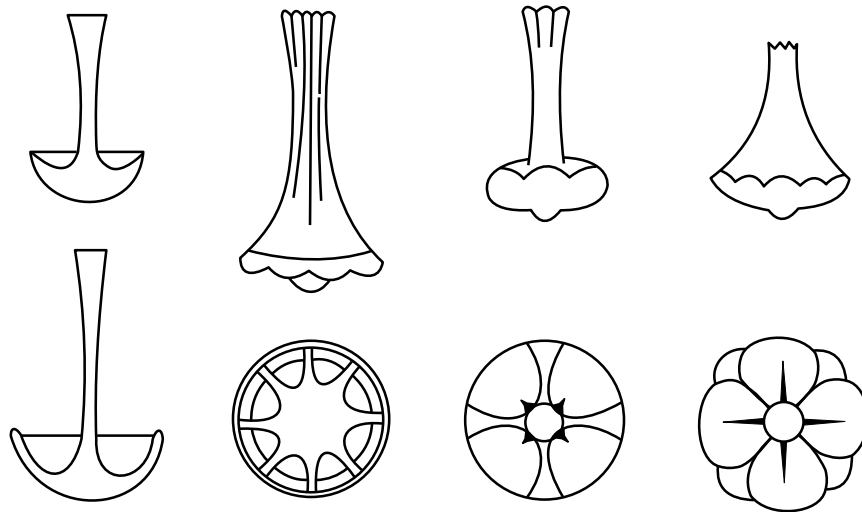


Fig. (2). Medusoid drops of gelatin [71].

The kinematics of jellyfish relate to another bio-pulse mechanism example in nature (Fig. 3). The jellyfish acquires a thrust force almost by pumping movement; however, it possesses a complex movement pattern and appearance because of its delicate body structure [72]. It squeezes its body to push water from the bottom. The displaced water creates a vortex. This propels it through the water. The jellyfish pauses in-between contractions so that the vortex accelerates the moving distance with each contraction. Rather than moving continuously through water while swimming, the jellyfish uses a critical pause between the radial contraction and expansion of its bell-shaped body to create a vortex ring in

water that pushes it forward. Muscles are used for the contraction of the body, which sheds the first vortex and pushes the animal forward; the mesoglea is so elastic that the expansion is powered exclusively by relaxing the bell, which releases the energy stored from the contraction. By doing so, a second vortex ring rolls under its body and it begins to spin faster. It then refills the bell and is pushed up against the centre of the body, giving it a secondary and ‘free’ boost forward. The mechanism, called passive energy recapture, only works at low speeds and relatively small body sizes, allowing jellyfish to travel 30% farther on each swimming cycle.

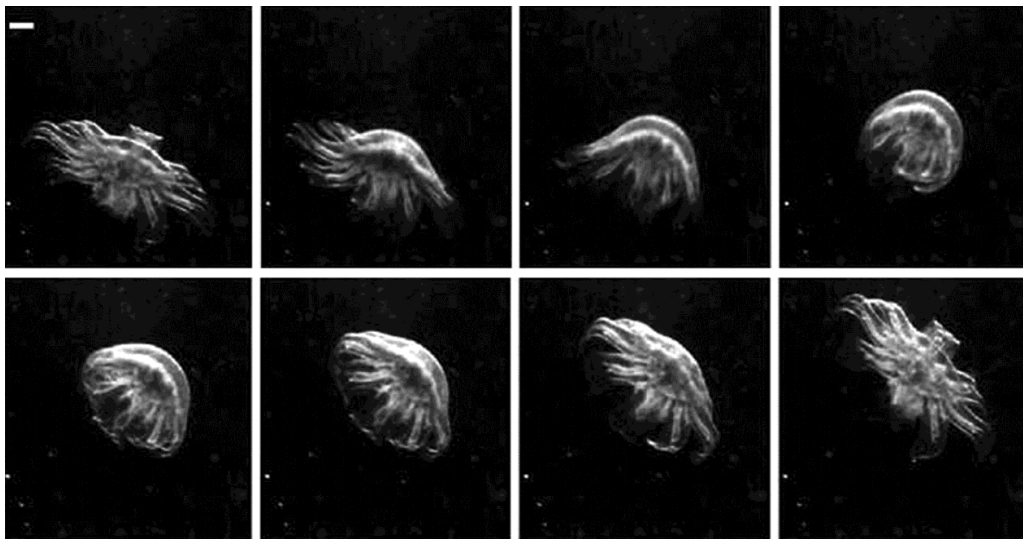


Fig. (3). Jellyfish kinematics.

5. CASE STUDY: HIGH-RISE AIRFLOW SYSTEM

The following case study exemplifies the preliminary design and simulation of a high-rise hybrid structure of 250 m height and 25 m diameter, which has a lightweight load-bearing system and incorporates a kinetic core mechanism to improve the environmental conditions of the building spaces and the surrounding high density urban areas, through vertical airflow, as shown in Fig. (4). The high-rise steel structure is principally an outrigger system with truss diagonals and vertical pretensioned cables at the outer perimeter [73]. The development of the high-rise kinetic structural mechanism, that supports upward air movements, follows a concept related to natural organisms' behavior. In this frame, the jellyfish movement pattern detailed in the section above, is applied on the structure's kinematics and materiality. The design proposes vertical PETG lamellas interconnected with prestressed ethylene tetrafluoroethylene, ETFE, membranes, in order to utilize the elements' elastic residual capacity in bending,

stretching and buckling to generate motion. The kinetic mechanism is envisioned to operate as an urban ventilation chimney for air polluted cities and contribute to microclimate improvements. The design proposal results from the integrative development of the structural elements that have inherent geometrical and mechanical features of modular assembly, reliability under differing heights and environmental conditions, re-usability and prefabrication.



Fig. (4). High-rise building with airflow core.

5.1. Primary Structure

The structure is divided over the height into units of 20 m, each containing five functional levels. The primary structure consists of an outrigger system of six radial vertical trusses, spanning between the core and the building perimeter (Fig. 5). Vertical cables are connected at the perimeter of the structure with the truss diagonals at the respective points. The horizontal levels comprise of three ring members, at the core, mid-span and perimeter, and the radial beams. All axial

beams are fixed to the ring members. Additional diagonals, between the members, increase the stiffness of the horizontal planes. Dimensioning the structural members has been based on Eurocode 3. A vertical load of 5 kN/m^2 and a horizontal one of 1 kN/m^2 have been considered for the analysis. The truss diagonals consist of circular hollow sections of $36/1.5 \text{ cm}$, the outer and middle ring members, of HEB450, and the inner ring members, of UPN320 sections. The vertical cable pairs have a diameter of 8 cm .

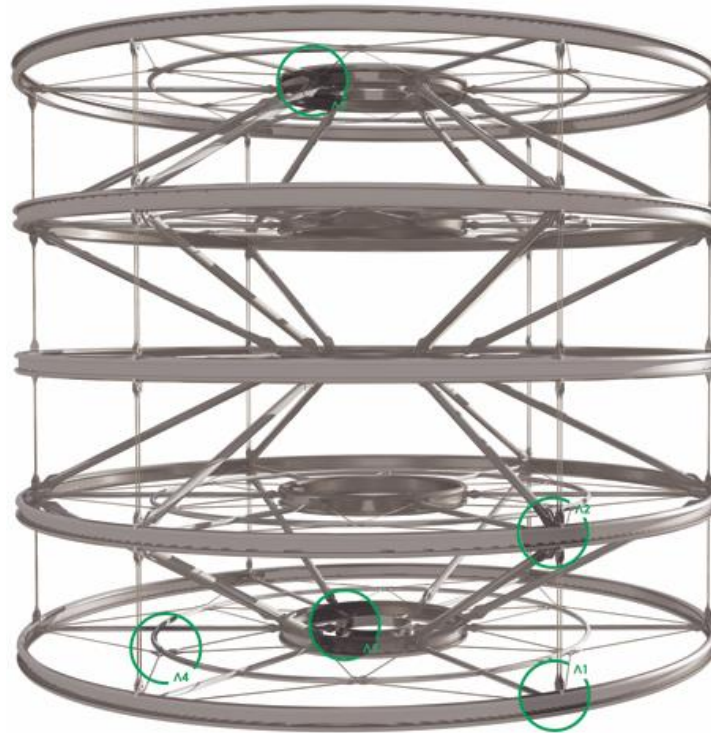


Fig. (5). Primary structure unit.

The structural system has been investigated in its load-bearing behavior with the Finite-Element software program SAP2000. In the nonlinear analysis conducted, the cables have been initially modelled as frame objects with a zero compression limit. The system develops primarily bending deformations, with fundamental period of 3.97 s . The maximum horizontal deformation of the structure amounts to 29 cm . Respective maximum stresses of the members for uniform vertical and horizontal loading correspond to a maximum axial force of 68638.63 kN in the diagonals; 58364.72 kN in the ring members; 58958.63 kN in the radial beams, and; 33182.54 kN in the cables. The ring members develop a maximum bending moment of 2013.24 kNm and the radial beams, 2715.63 kNm .

5.2. Secondary Kinetic Mechanism

The core of the structure enhances the vertical air circulation through an enclosed kinetic mechanism. Its morphology investigation was based on principles of aerodynamics and the variation of the inner space diameter so as to increase the air velocity and avoid turbulence effects. The kinematics of the jellyfish has been analysed and decoded for the development of the kinetic mechanism of the structure. The latter would contribute to an increase of the impulse of the airflow over the height. Therefore, the surface elements of the mechanism are contracted and expanded for the required impulse development of the airflow. The mechanism units are divided in pairs of 'bubbles'. In a contraction bubble, incoming air is enclosed and temporarily stored. In an expansion bubble, the stored air is vertically channelled. The contraction process of the air suction bubble induces expansion of the subsequent bubble, *i.e.* inverse structural transformation, so that the air is further channelled inward (Fig. 6). Both bubbles act inversely in a proportionate manner. The surfaces are placed between three ring members. The ring members on both edges have constant diameter and absolute position; the middle one varies its alternates on the vertical axis so that the process of transformation of each element during contraction and expansion is preserved.

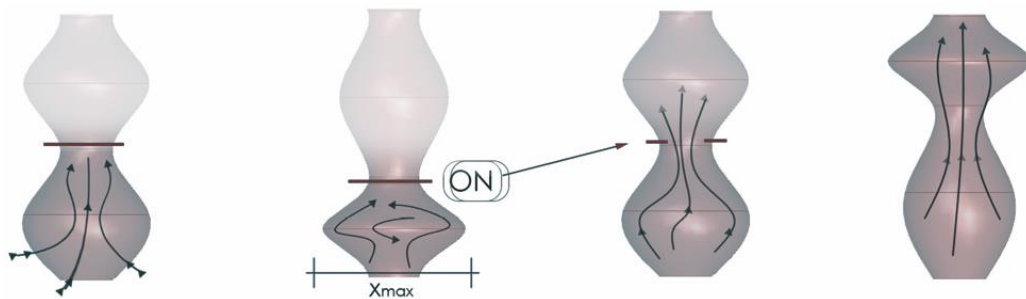


Fig. (6). Kinetic mechanism bubbles-unit transformability.

The mechanism surface consists of bending-active PETG lamellas of 20 m length, 10-30 cm width and 10 mm thickness that are interconnected with prestressed ETFE membranes and supported by the ring members on the vertical axis. The lamellas are bended to their initial position. They are characterized by high elasticity, tension strength and residual stress behaviour, enabling inverse transformations following uploading. The latter is primarily utilized at the intermediate stage of motion, at the point when the bubble reaches its maximum level of contraction following the air input. At this stage, the elastic energy stored resets the element at the initial position, resulting in expansion of the bubble.

The oscillation of the elements and the development of impulses for the vertical airflow within the mechanism activate subsequent motions of the consecutive bubble units. The impulses developed may induce an acceleration of the airflow with possible energy utilization. The building levels and the kinetic mechanism are placed at 5 to 25 m above ground, allowing introduction of the airflow from the area below. The upward airflow is supported over the height through differentiation of the air pressure at the respective technical storeys of the building (chimney effect) (Fig. 7). In addition, horizontal pumps are placed at these levels for air suction.

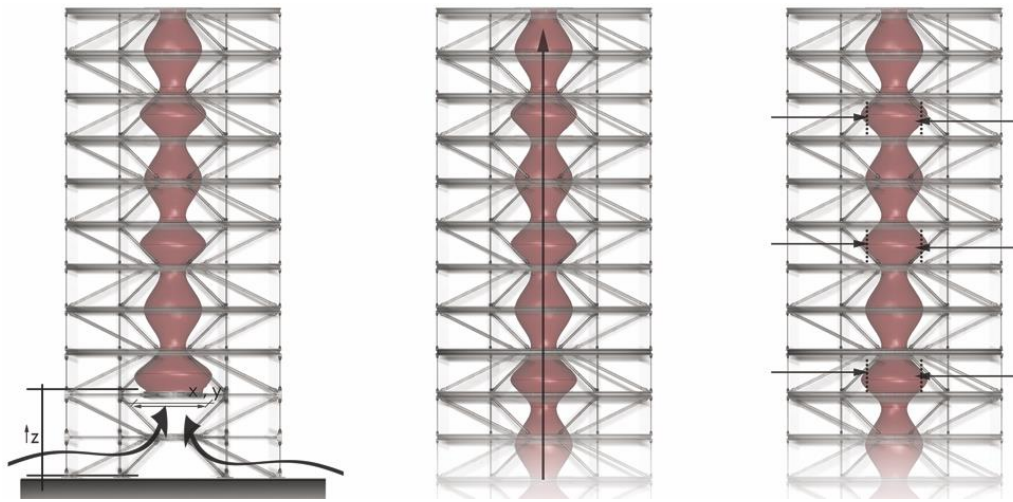


Fig. (7). Vertical air ventilation concept.

5.2.1. Simulation Analysis

The digital simulation of the bending-active structure aims at verifying the conceptual behavior of the core mechanism, as well as providing a representation of the kinetic mechanism of the digital prototype using parametric design logic. The parametric design software Grasshopper and the live physics engine software Kangaroo were used for the preliminary simulation of the kinetic structure. During the simulation process, the initial geometrical form, the parametric associative control, as well as the physical properties of the overall structural materiality were taken into consideration. In terms of geometrical and physics-based parametric control and behavior, the structure was initially examined through isolation of one pair of bubble units focusing on the curvilinear bending-active stripes interconnected with prestressed ETFE membranes, and then the structural system as a whole (synthesis of many pairs).

The structure was examined by classifying its elements into two main categories,

the PETG elastic lamellas acting as bending-active members and the prestressed ETFE membranes that provide stabilization and exercise control on possible deformations of the interconnected elastic units. These are associatively related and physically encoded based on forces including bending, pretension, gravity (self-loading), spring force and vertical rising wind flow.

The PETG lamellas and their elasticity were digitally simulated using bending-active behavior rules. The ETFE membrane was also digitally simulated, keeping the bending elements together, while maintaining the ability of its shape to be altered, due to its elastic properties. Analytically, the procedure involves the design definition of curved shape stripes with thinner cross section at both ends, as well as in the middle. To reach this outcome, a parametric division was created, into which two imaginary lines were designed to connect points and turn them into segments, in order to produce the 2D curved stripe. At the end of each line that represents the points of connection, the membrane consists of segments that are created in the empty space between the stripes. The deformed curved shape appears in two and three dimensions, representing the kinematically active position of the whole system. Initially, this is achieved by the trend of alignment of the curved stripes in straight line using any force or pressure. In order to undergo a respective bending alteration and keep the stripes in the initial bending active position, their edges are anchored to a fixed-section ring, while the points in the middle are joined to a smaller fixed-section ring, enabling vertical movement. The two rings at the ends are positioned in such a way that the distance between them is smaller than the length of the stripe in straight position. Therefore, the last two rings, which are positioned at the edges of the bubble pair units, place the whole system in an initial compression position, and enable energy to be stored in the elastic material of the bending stripes. Consequently, the system is already placed in an active position, which is controlled and simulated by applying spring behavior on the basis of Hooke's Law of elastic stress-strain behavior [61]. Regarding the force or pressure applied on these elastic members, there is a proportional distortion with the help of the middle ring that moves vertically. When it reaches the maximum amount of distortion, the energy stored is used to reset the system to the initial shape and position.

The simulation of the stripe members' behavior is achieved by applying bending and spring forces, while the physical behavior of the membrane is simulated using spring and wind forces. An external parameter of wind force is applied. When this enters the interior of the structure, it creates a distortion of the area surrounded by the stripes and the membrane, which causes the vertical movement impulsion of the stripes. This behavior expands to the lower bubble inner area, creating a respective contraction of the upper inner region. As a consequence, the stored energy, derived from the structural materiality, works as an actuator of the system,

forcing the shape to reach a recovery position, through the method of pulse (Fig. 8).

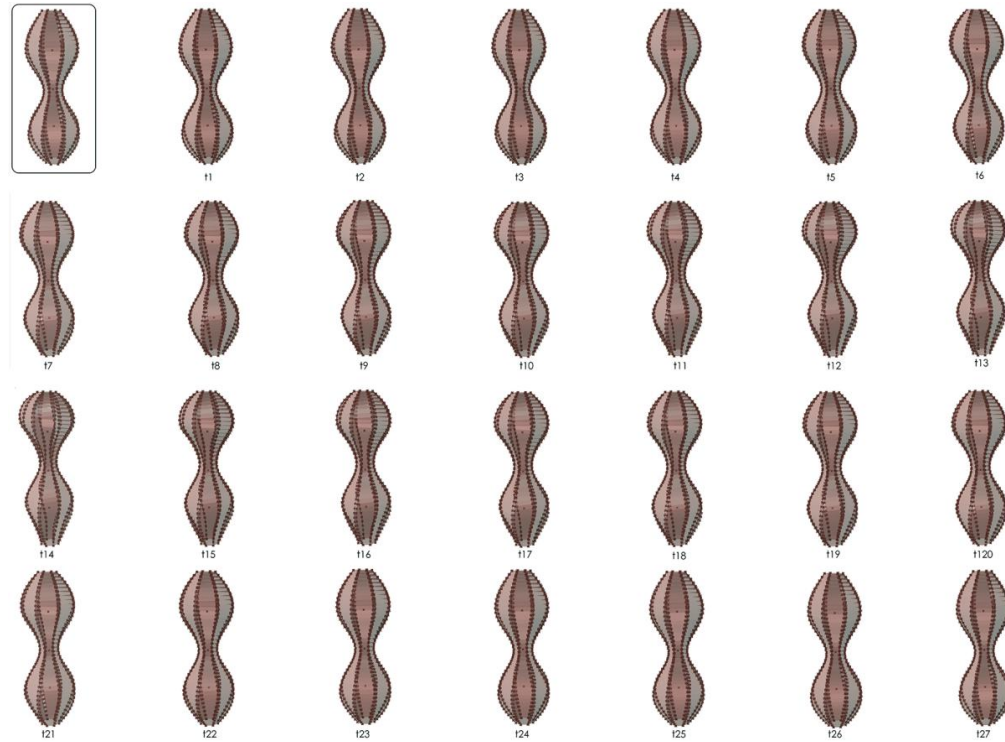


Fig. (8). Simulation steps indicating the transformability of a bubble pair.

Consequently, the investigation procedure enables decoding of the material in view of the members' interaction behavior with different environments. In the case example examined, structural deformation is influenced by external forces, due to vertical upward wind flow and self-loading conditions. This simulation process provided a series of system deformation scenarios based on motion frequency and shape alteration, induced by wind speed. The results represent possible behavior of the prototype under the use of force or pressure. Therefore, a relation between modelling and realization was created through the process of digitization and simulation.

CONCLUSIONS

The development of kinetic structures is presented in the current chapter. The initial visions on kinematics, realised thus far, are primarily based on a hard-mechanical approach, often lacking real flexibility with regard to the system's

spatial transformability, mechanical simplicity and energy efficiency. Considerable improvements in these aspects may be achieved through a soft-mechanical approach, while the biomimetic design comprises the driving mode of operation in interdisciplinary research and design environments. An investigation, abstraction and application of respective functional principles available in nature may well provide fundamental principles in the design of kinetic structures in architecture. In this respect, recent examples derive mainly from the study and implementation of plant movement patterns in design. Following an overview of respective structures' development and simulation methods, the authors further present bio-pulse oscillation principles on the basis of the human cardiac operation for blood circulation, fluid drops and the jellyfish motion behavior. In exemplifying a related biomimetic design process, a high-rise airflow structural concept based on an incorporated kinetic soft-mechanics mechanism has been developed. The jellyfish movement pattern has provided the kinematics, realized by units of transformable bubble pairs, arranged vertically within the structures core. The bubbles consist of bending-active members interconnected with prestressed membranes and ring members. Utilization of the elastic material properties of the members enables sequential motions through contraction and expansion of the bubbles in support of the vertical airflow. The project proves that the biomimetic design is in a position to identify and transfer innovative principles to the design of kinetic structures.

CONSENT FOR PUBLICATION

Not applicable.

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CONFLICT OF INTEREST

The authors confirm that this chapter contents have no conflict of interest.

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Truss Material Reduction Provided by the Golden Ratio

Ulisses Targino Bezerra*

Federal Institute of Paraíba-IFPB, Civil Construction, Av. Primeiro de Maio, 720, Jaguaribe, zipcode 58.015-435, João Pessoa-PB, Brazil

Abstract: Trusses are designed for supporting loads while ensuring reduction in material consumption and providing stability. Following these principles, nine types of structural trusses were designed using the Stiffness Method. Details of the trusses include: 20 m span, 1 m height, concentrated load of 10 kN (at the centre of the structure), with profiles composed of circular steel bars (ASTM A36, 210 GPa for modulus of elasticity). The trusses differed from each other specifically in the height (truss)/length (chord) ratio. The ratio values varied between 44.44 cm and 100.00 cm. The profiles were sized for carrying solely loads anticipated in the structural design, with no unloaded cross sections. The results included material consumption for each structural type: TRUSS 1 (110.39 kg), TRUSS 2 (106.26 kg), TRUSS 3 (105.04 kg), TRUSS 4 (104.25 kg), TRUSS 5 (103.83 kg), TRUSS 6 (105.63 kg), TRUSS 7 (105.91 kg), TRUSS 8 (108.47 kg), and TRUSS 9 (113.38 kg). The results indicated that the truss with the lowest material consumption also used a height/length ratio corresponding to the Golden Ratio, a value frequently encountered in nature. This Golden Ratio provided a minimal consumption of material, while maintaining structural stability. As for strain, nothing was identified (unfortunately!). Nowadays, it is not surprising when this value is identified in nature, but when the Golden Ratio is indirectly encountered in an essential technical human activity, it is relevant; not for human advantage, on the contrary, nature seems to be communicating something to humanity in its own language. Would this language be what is currently called biomimetics?

Keywords: Golden Ratio, Truss, Design of Structure.

1. INTRODUCTION

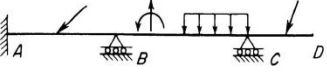
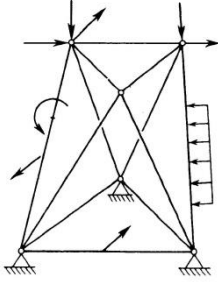
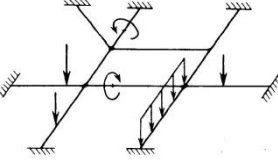
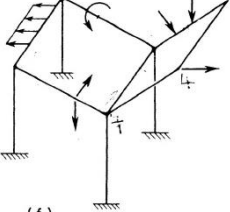
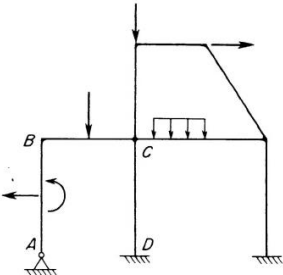
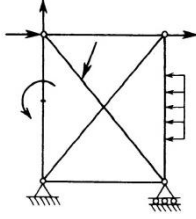
Galileu Galilei made a mistake in the publication of *Discorsi e dimostrazioni matematiche*, intorno à due nuove scienze, in 1638 [1], he imagined that the neutral axis of a beam would be located at its lower face. This error was only

* **Corresponding author Ulisses Targino Bezerra:** Federal Institute of Paraíba-IFPB, Civil Construction, Av. Primeiro de Maio, 720, Jaguaribe, zipcode 58.015-435, João Pessoa-PB, Brazil; Tel: 0558336121200; E-mail: dartaorios@yahoo.com.br

corrected 40 years later, in 1686, with the posthumous publication of Edme Mariotte, who, after several misconceptions, demonstrated that the neutral axis is located at the middle of the beam height [2], as is known today. The presence of some concepts of nature in humankind is not new [3], after this period, some researchers, as Engel [4] and Silver *et al.* [5] developed and integrated the concepts of civil structures and nature.

If both scientists Galileu Galilei and Edme Mariotte had been devoted to the observation of a tree contemplating the passage of the wind, the neutral axis would certainly have been identified more easily and solving problems through biomimicry would already be fully established in the present day humankind. But it is never too late! Framed structures, those which are composed of straight frames and joints, are divided, regarding stability, into 6 types according to Table 1 [6, 7].

Table 1. Types of framed structures according structural analysis.

Type	Geometry	Type	Geometry
Beam		3D truss	
Grill		3D frame	
2D Frame		2D Truss	

Source: adapted of Gere and Weaver [6].

A particular model belonging to the “plane truss” type was conceived by the American Thomas Willis Pratt (Fig. 1), in the 19th century [8].



Fig. (1). American Civil Engineering Thomas Willis Pratt (1812-1875) [8].

As all truss structures, Pratt trusses are composed by combination of triangles, as shown in Fig. (2).

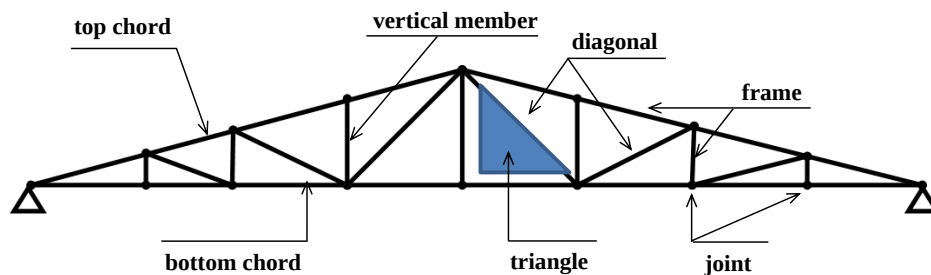


Fig. (2). Composition of a typical plane truss according Pratt concept.

In plane trusses, external loads are transmitted to the joints, which pass them to the frames through normal forces of tension and compression. The distribution of frames can follow any type of geometry, since internal parts of the structure are triangles of any shape.

Some authors, like Leonhardt and Mönnig [9] and Rocha [10], and some standards, both from Brazil and from Europe [11 - 14], establish criteria regarding diagonal sizing. These studies conducted in 1899 with the conception of the Ritter

truss, that later evolved to the Ritter-Mörsch truss [15].

The inclination between the bottom chord and the diagonal must be greater than 45° , reaching up to 60° (maximum). However, with no specific reason, current criteria are related only to the structural stability. In other words, the standards and authors do not establish criteria based on reducing materials consumption.

Variations in boundary conditions, aesthetic aspects, material variations or sustainability criteria are not considered here. It can be stated that these variations do not interfere in the final relative analysis, but only in the absolute numbers.

However, though coming from the group of the irrational numbers, such as the number π (3.14159265...), the Euler's constant e (2.71828182...), the Euler-Mascheroni constant (0.57721566...), *etc.*, the number ϕ (1.61803398...) the Golden ratio, has aroused man's attention, as the number that is most used by nature in its several manifestations [16, 21]. The Golden ratio is discussed here in a different line of thinking. Though the common literature generally seeks to identify any close relationship of ϕ to the structures and natural processes involved, this work identified, spontaneously, that the Golden ratio leads to reduced material use in the design of Pratt trusses.

Thus, this work aimed to investigate the relation between the truss height and the spacing of its vertical members, while seeking the lowest material consumption possible while obviously, maintaining structural stability. In form of a question: what is the relation between the height of a truss (with parallel chords) and the spacing of its vertical members that leads to the largest economy in materials used?

2. PRATT TRUSS MODELS

In this work, Pratt truss models were designed. The structures have parallel chords, 20 meter lengths, at 1 meter high, and support a concentrated load of 1,000 kgf (10 kN), at the midspan (Fig. 3).

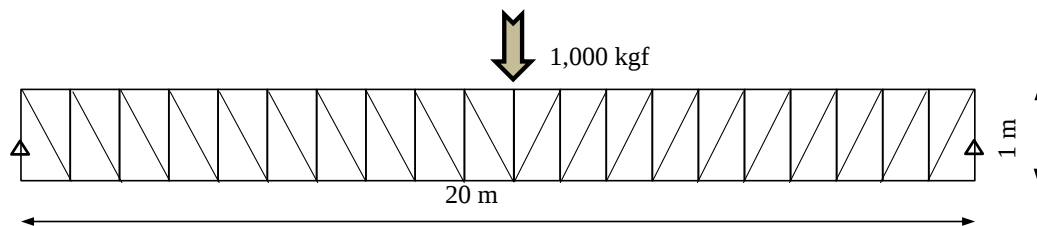


Fig. (3). Investigated truss: Pratt model with concentrated charge in centre.

For designing the trusses; in search of the most economic sizing, proportions between truss height and post spacing were varied. Thus, the only difference between the investigated trusses was the vertical members spacing.

For calculating the internal forces supported by the truss frames, the Stiffness Method was used with SAP90 software [17]. The frames were sized as solid circular bars and their diameters were exactly designed to support the prescribed loads. Although any material could have been used, ASTM A36 steel was adopted, having a yield strength of 2,500 kgf/cm² (250 MPa), and a Modulus of Elasticity of 2,050,000 kgf/cm² (205 GPa). Due to the fact that structures were plane trusses, only two types of forces were found in the structural design:

(i) Tensile force: in this case, design area was directly calculated through Equation 1 [18]:

$$A = F/\sigma \quad (1)$$

Where: A = cross section area of the solid circular bar (cm²);

F = calculated force in structural design (kgf); and

σ = yield strength of ASTM A36 steel (2,500 kgf/cm²).

(ii) Compressive force: for the force of compression, Equation 2 (Euler buckling formula) was considered [19, 20]:

$$P_{cr} = (\pi^2 E I) / L^2 \quad (2)$$

Where: E = modulus of elasticity (2,050,000 kgf/cm²);

I = moment of inertia (cm⁴); and

L = buckling length of the frame (cm).

From the moment of inertia, the radius of the bar was determined and, consequently, its cross section area.

Nine trusses were designed with different height/spacing proportions. Four trusses were calculated with their proportions being higher than the Golden ratio and four with their proportions being lower than the Golden ratio, as shown in Fig. (4) and Table 2.

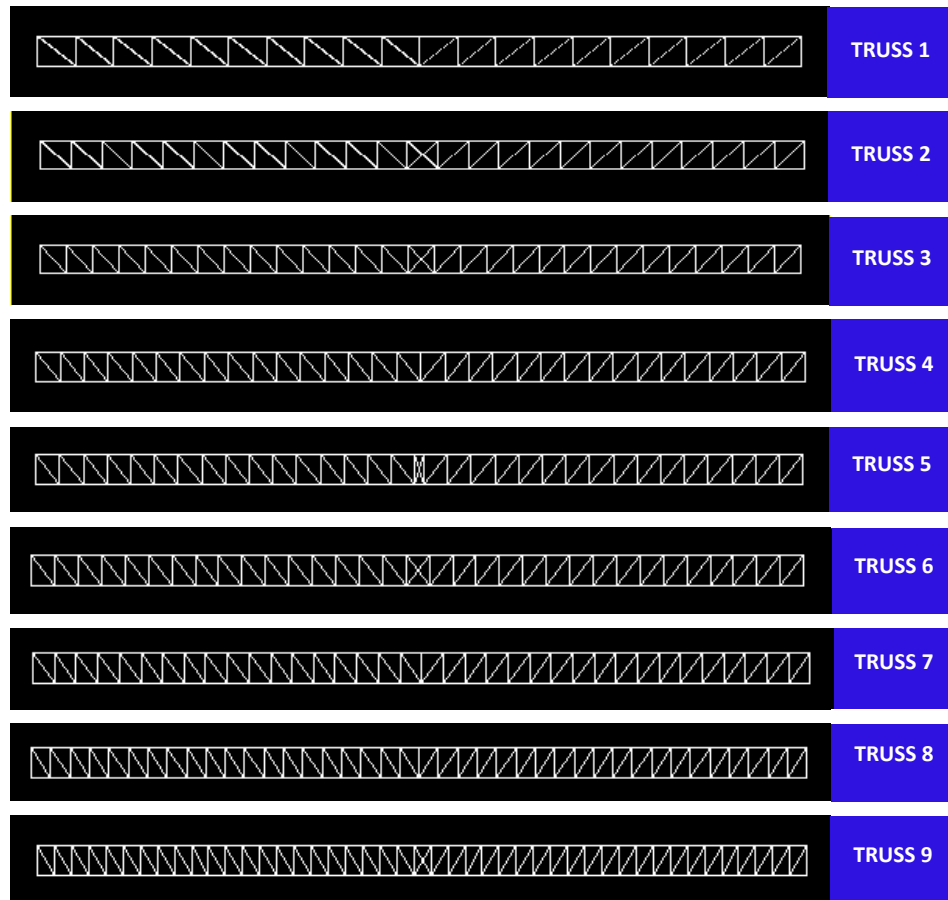


Fig. (4). Representation of investigated trusses and its variations of post spacing.

Table 2. Investigated truss models (constant height of 1 meter).

Truss Model	Post Spacing (cm)	Height/Spacing Proportion (Dimensionless)	Angle (°)
TRUSS 1	20 x 100.00	1.000	45.00
TRUSS 2	25 x 80.00	1.250	51.34
TRUSS 3	29 x 68.96	1.450	55.41
TRUSS 4	32 x 62.50	1.600	57.99
TRUSS 5	32 x 61.80 + 1 x 22.29	1.6180339985*	58.28252518
TRUSS 6	33 x 60.61	1.650	58.78
TRUSS 7	36 x 55.56	1.800	60.94
TRUSS 8	40 x 50.00	2.000	63.43

(Table 2) *cont....*

Truss Model	Post Spacing (cm)	Height/Spacing Proportion (Dimensionless)	Angle (°)
TRUSS 9	45 x 44.44	2.250	66.04

Note: *Golden Ratio.

3. PRATT TRUSS ANALYSIS

The design of every truss model used calculated loads in each frame, as well as the steel profiles (solid circular section) to be used for structural stability maintenance. No safety factors were considered in the design process.

As an example, Table 3 shows the results for TRUSS 1 (only this set of results is presented, as including the results for every truss model would not fit in this document).

Table 3. Forces in TRUSS 1 frames.

Frame Number	Force (kgf)	Length (cm)	Radius (cm)*	Section (cm ²)**	Volume (cm ³)	Mass (kg)***
1	0.00	100.00	-	0.00	0.00	0.000
2	500.00	100.00	-	0.20	20.00	0.156
3	1000.00	100.00	-	0.40	40.00	0.312
4	1500.00	100.00	-	0.60	60.00	0.468
5	2000.00	100.00	-	0.80	80.00	0.624
6	2500.00	100.00	-	1.00	100.00	0.780
7	3000.00	100.00	-	1.20	120.00	0.936
⋮	⋮	⋮	⋮	⋮	⋮	⋮
21	- 500.00	100.00	0.74	1.74	174.11	1.358
22	- 1,000.00	100.00	0.89	2.46	246.23	1.921
23	- 1,500.00	100.00	0.98	3.02	301.57	2.352
24	- 2,000.00	100.00	1.05	3.48	348.22	2.716
25	- 2,500.00	100.00	1.11	3.89	389.33	3.037
26	- 3,000.00	100.00	1.16	4.26	426.49	3.327
27	- 3,500.00	100.00	1.21	4.61	460.66	3.593
⋮	⋮	⋮	⋮	⋮	⋮	⋮
75	707.11	141.42	-	0.28	40.00	0.31
76	707.11	141.42	-	0.28	40.00	0.31
77	707.11	141.42	-	0.28	40.00	0.31
78	707.11	141.42	-	0.28	40.00	0.31

(Table 3) cont....

Frame Number	Force (kgf)	Length (cm)	Radius (cm)*	Section (cm ²)**	Volume (cm ³)	Mass (kg)***
79	707.11	141.42	-	0.28	40.00	0.31
80	707.11	141.42	-	0.28	40.00	0.31
81	707.11	141.42	-	0.28	40.00	0.31
					Total	110.39

Notes: * In the case of compressive forces, the radius was determined first;

** All cross sections are composed using circular steel profiles; and

*** The specific gravity of the steel was considered equal to 7.8 g/cm³.

The total mass of TRUSS 1 equals 110.39 kg.

Table 4 and Fig. (5) contain data for the masses of all trusses.

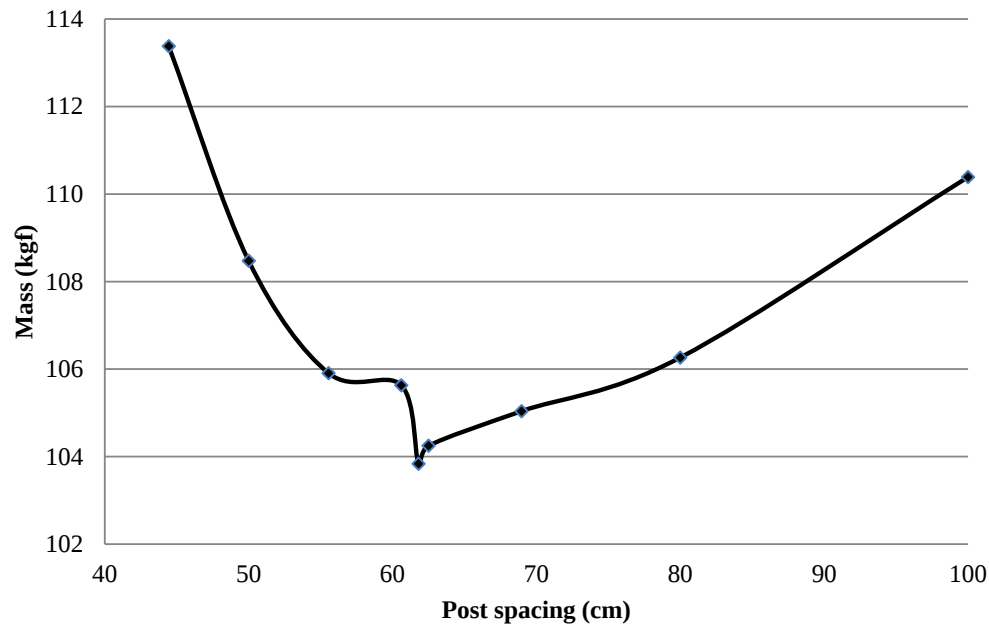


Fig. (5). Graph presenting mass (kg) *versus* spacing between truss post spacing (cm) after the structural calculation.

Table 4. Masses of the truss models.

Truss	Mass (kg)
TRUSS 1	110.39
TRUSS 2	106.26
TRUSS 3	106.04

(Table 4) cont.....

Truss	Mass (kg)
TRUSS 4	104.25
TRUSS 5	103.83
TRUSS 6	105.63
TRUSS 7	105.91
TRUSS 8	108.47
TRUSS 9	113.38

The difference between the heaviest and the lightest truss was 9.19%. In technical terms, such a percentage is not so significant, because other factors are preponderant when regarding structural design, for example: safety factors, standardization of commercial steel profiles, reduction of welding points, workforce incidence in structure construction, *etc.* However, the major coincidence between the post spacing, represented by the Golden ratio, and the truss structure that consumes less material is worth noting. Nature seems to be saying that this number must always be observed in human praxis.

Another aspect that belongs to structural design, and which should never be forgotten, refers to strain magnitudes. The strain presented in the investigated trusses, at the centre of the structure (maximum value), is presented in Fig. (6).

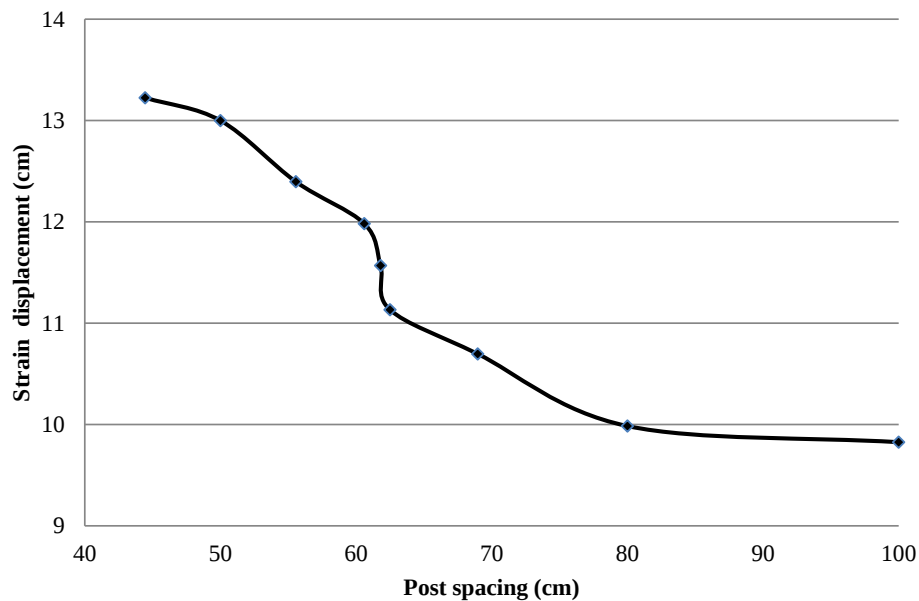


Fig. (6). Graph presenting strain displacement (cm) *versus* post spacing (cm) after structural calculation.

In Fig. (6), a strain reduction tendency can be observed for higher height/spacing proportions, in other words, larger spacing between vertical truss members. This behaviour trends towards greater stability for higher proportions.

For the proportion equivalent to the Golden ratio, the strain is of 11.57 cm, which corresponds to a ratio of chord length to strain displacement equal to 1/173.

In Table 2, the values are presented for the angle between the bottom chord and the truss diagonals. The aforementioned standards and authors cite ideal angles values ranging from 45° to 60°. In this work, the Golden ratio leads to an angle of 58.28° (= tangent of Golden number), as being the ideal angle for maintaining structural stability and reduced material consumption (Fig. 7).

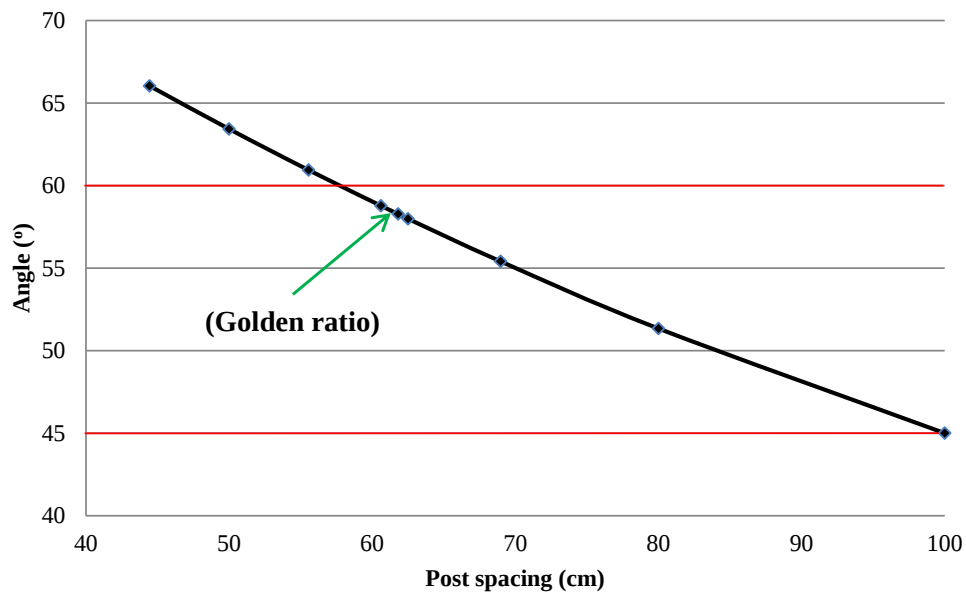


Fig. (7). Graph presenting angle (°) versus post spacing after structural calculation (see the limits suggested by some authors [9 - 14]).

The ideal angle, considering both structural stability and reduction of material consumption is found within the interval proposed by the aforementioned authors and related standards.

CONCLUSIONS

The Golden ratio has been employed by nature for many millions of years and by humans during millennia. The disciples of Pythagoras were likely the first to

identify the Golden Ratio. Thus, there is no surprise when the value is identified in some peculiarity of nature. However, when this value is identified indirectly in an essentially human activity, it becomes an interesting fact, an attempt by nature to communicate something to humankind, and not a deliberate human choice of the value.

The conception of Golden Ratio proportioned height/spacing Pratt plane trusses leads to structural dimensioning that involves reduced material consumption; yet without compromising stability. Material reduction in this work reached 9.19%, yet may depend on the height spacing proportion adopted. If such values are at times insignificant for humanity, in nature they are not wasted.

However for deformation values, the most appropriate post spacing is the largest, and adopting the Golden ratio as a criterion of choice for this aspect alone would present no advantages, not all purposes come with certain success.

In a process of pure speculation, the Golden Ratio can be write as:

$$1,618... = 1 + 0,618... = 1 + 1/1,618...$$

In other words: when you are the **SUM** of **UNIT** and the **INVERSE OF PERFECTION**, you are: **PERFECT**.

The presence of the Golden Ratio in nature, should not be neglected but observed, in the sense of understanding what nature communicates to us in its own language.

This language is probably called: BIOMIMETICS!

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CONSENT FOR PUBLICATION

Not applicable.

CONFLICT OF INTEREST

The author confirms that this chapter contents have no conflict of interest.

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Complexity and Adaptability in Nature and Society

George Rzevski*

Centre for Complexity and Design, The Open University, Milton Keynes, UK

Abstract: This chapter deals with the issues related to the complexity and adaptability of human to nature. What is complexity in a complex world? Seven concepts/properties of complexity are presented. The world created by humans demands of itself changes of posture relative to its adaptation, without this, the planet Earth does not seem to be a friendly environment to live. Thus the science of complexity is necessary to make everyday relations, once marked by simplicity, occur without trauma, since they are necessarily complex. What does it take to adapt to the world of complexity? Coping with disruptions, defending from attacks, resolving conflicts, correcting drift into failure, and avoiding stagnation. Necessary tools for adapting the technology for designing complexity into organizations, processes and products references are presented: architecture, multi-agent software works, organizational, and process design cases, engineering design cases, *etc.* It is not known how the future will be, but certainly complexity will be one of its characteristics.

Keywords: Complexity, Adaptability, Nature, Society, Brain.

1. INTRODUCTION

After Darwin, we accept that evolution by natural selection shapes our physical environment. Those species who adapt to changing environment, survive. Those who don't – perish.

Fig. (1) shows some aspects of the brain structure.

Natural evolution favours complexity. Homo Sapiens developed into a dominant species primarily due to emergent properties of their highly complex brain, as exemplified by cognitive, emotional and social intelligence, creativity, ability to innovate, communicate and bond, to mention but a few exceptional human brain features.

* Corresponding author George Rzevski: Centre for Complexity and Design, The Open University, Milton Keynes, UK; Tel/Fax: 447525746106; E-mails: george@rzevski.net

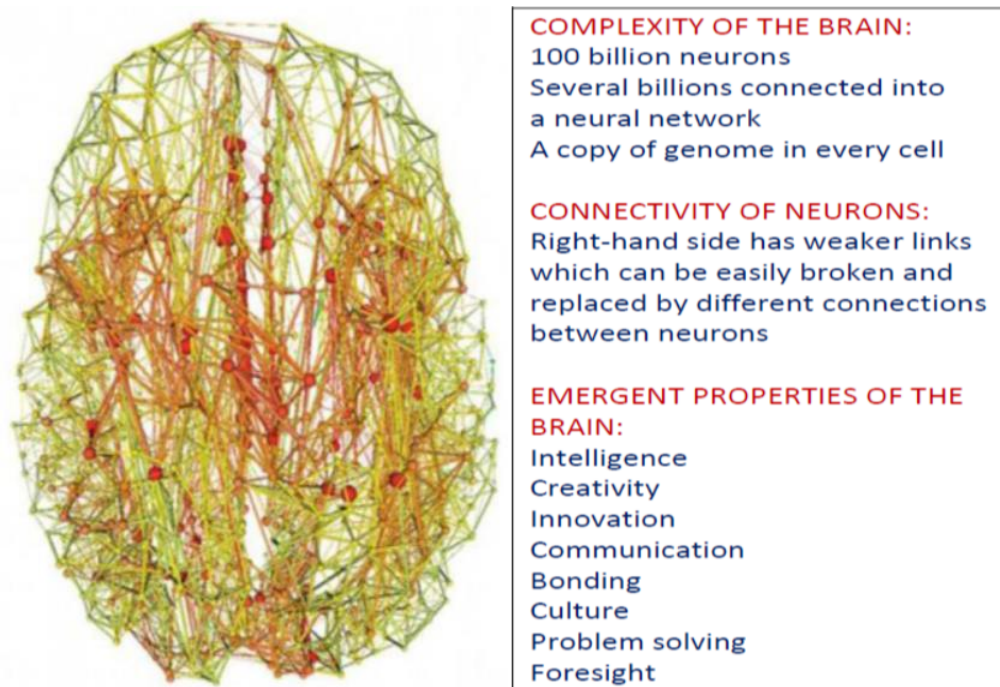


Fig. (1). *Homo sapiens* brain.

Driven by socio-technological evolution, our social, economic, political and technological environments have now reached a very high level of complexity [1], as illustrated in Fig. (2).

Social organizations that operate in complex geopolitical or socio-technological environment should be designed to adapt to changes in their environments rather than resist them [2]. Consider also social organizations such as nations that are subject to threats of terrorist or cyber-attacks or military attacks from other nations. Should we not design these social systems to adapt when attacked, *e.g.*, to dynamically regroup and re-deploy internal resources to fight attackers? This would make vulnerable systems resilient to attacks.

From the new science of complexity, we know that only complex organizations can be adaptive and resilient. We should learn therefore how to design complexity into organizations - a counterintuitive idea in a world where conventional wisdom prefers simplicity.

Let us first refresh our understanding of complexity.

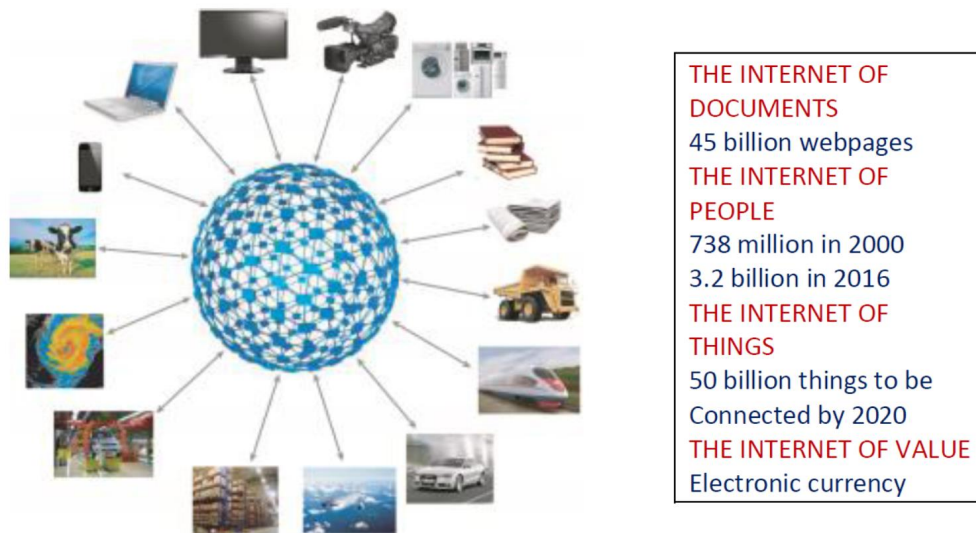


Fig. (2). Complexity of the man-made global network is growing at a high rate.

2. WHAT IS COMPLEXITY?

Complexity is a property of an open system that consists of many diverse, partially autonomous, richly interconnected components, often called Agents, has no centralised control, and whose behaviour emerges from the intricate interaction of agents and is therefore uncertain without being random. The autonomy of agents is limited by constraints imposed on them by the system to which they belong.

The level of complexity of a system depends mainly on the autonomy of its agents and agent connectivity. The greater the degree of autonomy of agents and their connectivity (density and flexibility of connections), the higher is its complexity.

The use of the term complex is often confused with the term complicated. To understand the differences, let's examine the roots of the two words. "Complicated" uses the Latin ending "plic" that means, "to fold" while "complex" uses the "plex" that means, "to weave." Thus, a complicated structure is one that is folded with hidden facets and stuffed into a smaller space. On the other hand, a complex structure uses interwoven components that introduce mutual dependencies and produce more than a sum of the parts.

The father of complexity science, Ilya Prigogine, stipulates that a system is complex if its global behaviour emerges from the interaction of local behaviours

of its components [3]. Prigogine in his writings emphasises that the behaviour of a complex system cannot be predicted and that, in general, the future is not given [4]; it is being created by actions of all those participating in the working of the Universe. He discusses the examples of complex systems from physics and chemistry, including molecules of air subjected to a heat input, autocatalytic chemical processes and self-reproduction of cells. Emergent behaviour of complex systems is widely covered in the literature [5] and applied to many domains, including economics.

To locate complex systems on a map of predictability, I proposed the following system classification (see Table 1 below), in which complex systems are placed between random and deterministic systems [6].

Table 1. Classification of systems.

Random Systems	Complex Systems	Deterministic Systems
Uncertainty = 1	$1 > \text{Uncertainty} > 0$	Uncertainty = 0
Random behaviour	Emergent behaviour	Planned behaviour
Autonomy of agents = 1	$1 > \text{Autonomy of agents} > 0$	Autonomy of agents = 0
Disorganized	Self-organizing	Organized
No control	Guided by norms, laws, rules	Centrally controlled
Random changes	Adapts and co-evolves	Designed not to change
Random movements	Operates far from equilibrium	Operates at equilibrium

3. SEVEN KEY PROPERTIES OF COMPLEXITY

3.1. Connectivity

Agents are richly interconnected enabling them to exchange messages and negotiate outcomes. Connections are sufficiently weak to enable the system to easily remove them when obsolete. Complexity of the system increases with the agent connectivity (connection density) and decreases with connection strength.

3.2. Autonomy

Agent autonomy is restricted by natural laws, rules and regulations. Complexity of the system increases with autonomy of constituent agents.

3.3. Emergence

The global behaviour of a complex system is unpredictable, it emerges from the

interaction of agents.

3.4. Nonequilibrium

As a rule, complex systems experience frequent disruptions of operation and are therefore unable to return to equilibrium between two consecutive disruptive events.

3.5. Nonlinearity

Due to nonlinearity of agent connections, the accumulation of many small, individually insignificant disruptions, may cause an extreme event – a catastrophe.

3.6. Self-organization

Self-organization is the golden property of complex systems. It enables them to achieve their goal under conditions of frequent disruptions by rapidly and autonomously adapt to changes in their environment.

3.7. Co-evolution

Perpetual self-organization aimed at adapting to the environment results, over time, in co-evolution of the system and its environment.

4. COMPLEXITY SCIENCE

4.1. Brief Overview

Complexity is recognised as a critical feature of contemporary life and a large research effort is devoted to the formulation of a new science of complexity. One way of conducting research into complexity is to build large-scale computer models of various complex situations and to observe how models react to a variety of inputs. Initial research results are very encouraging and they enable us to formulate tentative principles of complexity science, which may explain behaviour of many social systems such as businesses, administrations, nations, associations of nations, the global market and the geopolitical constellation.

Here is a selection of insights into behaviour of complex systems relevant to our discussions.

Perhaps the most important assertion is:

Our social, economic and political environments cannot be simplified because their complexity is a result of evolutionary forces, which are not under our control.

Therefore, to survive and prosper under conditions of complexity we must learn how to adapt to our environment.

To be adaptive a system must be able to perform the following activities autonomously (*i.e.*, without external intervention):

- i. Forecasting changes;
- ii. Detecting a change as early as possible;
- iii. Identifying which parts of the system will be affected; and
- iv. Rescheduling the affected part with the aim of eliminating or at least reducing consequences of the change.

By repeatedly adapting to its environment and, in turn, influencing it over a long period of time a complex system and its environment co-evolve.

5. ADAPTABILITY

5.1. Coping with Disruptions

Our complex economic, political and technological environment create frequent disruptive events, including frequent changes of demand and supply; cancellation or modifications of previously agreed deals, orders and promises; delays, failures and interruptions; security breaches, fraud, hacking, sudden change of political alliances, unexpected military interventions.

Frequently occurring and unpredictable, disruptive events prevent us from sensibly planning our work and life. Businesses and administrations have great difficulties in managing the allocation of readapt.

Under such conditions whilst rigidly structured systems experience difficulties, complex systems adapt and eliminate undesirable consequences of disruptions.

5.2. Defending from Attacks

Complex systems are remarkably resilient to attacks. The author's recent study of warfare from Napoleonic wars to the present day through the lenses of complexity science shows that, with few exceptions, nations who started a war, finished as losers. The reason is always the same – defending nations (being complex) are capable of self-organizing into flexible net-like structures and engage in guerrilla warfare capable of resisting and defeating any brute force. Societies follow similar

patterns of defence as biological immune systems.

Following the same idea, the author's team designed complex adaptive software capable of self-organizing in response to a cyberattack into a guerrilla-type defence network.

5.3. Resolving Conflicts

Complex systems can be designed to exhibit propensity for resolving potential conflicts by initiating negotiations as soon as seeds of conflict are detected. The important ingredient in conflict resolution is for parties in conflict to try to find a common ground, which is much easier in early stages of hostilities before resentments harden.

5.4. Correcting Drift into Failure and Avoiding Stagnation

Success tends to reduce alertness of agents and encourages the so-called drift into failure, which occurs when agents believe that small mistakes, sloppiness, fraud or simply lack of improvements, will not be noticed because every year is better than the previous. Therefore, it is very important to exercise a careful monitoring of behaviour of participants (agents) when everything is going well. By close monitoring of bankers during the seemingly unstoppable wealth growing period we could have avoided the financial crisis of 2008/2009 caused by subprime loan fiasco.

Once the crisis occurs, experiments show that it is necessary to do the opposite, to lift unnecessary restrictions to enable entrepreneurs to come up with original and unusual ideas how to get to the wealth creating wave as soon as possible – the exact opposite to what politicians did to bankers after the global financial crisis.

6. DESIGNING FOR ADAPTABILITY

During the last 20 years, the author has accumulated a rich practical experience in designing complexity into organizations, businesses and engineering products with a view to making them adaptable. Based on this experience, it is proposed here a set of key fundamental principles of the design for adaptability:

- i. To design an organization or a (business) process to be adaptive, the most important move is to make decision-making distributed. Centralised control and command system should be replaced by teamwork;
- ii. Team decision-making should be guided by company policies, rules and regulations rather than directed and controlled by a Chief Executive;
- iii. Restrictions to freedom of decision making of agents should be tuned finely by adjusting the quantity and rigidity/flexibility of policies, rules and

- regulations;
- iv. Provisions should be made for autocatalytic properties and for self-acceleration of processes that lead to effective adaptation. This can be achieved by allowing certain amount of experimentation with bold, innovative ideas and, most importantly, by planning a variety of alternative ways of achieving the specified goal;
 - v. Strengths of links between teams and between members of each team should be carefully planned to enable rapid re-adjustment in reaction to important events without excessive negotiation ripples. Typically, the communication links between members of a team must be strong whilst the strength of links between teams must be graded to reflect the closeness of team objectives;
 - vi. Enterprise ontology should be designed to contain domain knowledge required for effective operation of the organization;
 - vii. All human decision makers should be supported by highly adaptive agent-based systems and all routine decisions delegated to intelligent multi-agent technology connected to common Enterprise Network; and
 - viii. Physical objects (aircraft, cars, trucks, ships, cargos, pallets, parcels, components, *etc.*) constituting parts of the organization should be supplied with electronic tags and their environments (hangars, workshops, plants, warehouses, cargo holds) equipped with electronic tag readers so that physical objects can be connected to the same Enterprise Network.

Principles for designing adaptive products are the same if we accept that words used above such as “teamwork”, “chief executive”, “organization” are used as metaphors meaning “collaboration of components”, “centralised controller” and “product”.

7. TECHNOLOGY FOR DESIGNING COMPLEXITY INTO ORGANIZATIONS, PROCESSES AND PRODUCTS

The most effective technology for constructing complex systems which exhibit all features described in the previous section is multi-agent software [7].

In contrast to conventional software such as centralized schedulers, planners and optimizers, which from the start to the end follow algorithms, multi-agent software works primarily by exchanging messages: Intelligent Software Agents negotiate deals with each other, always consulting problem domain knowledge assembled in Ontology. Negotiations are conducted by a concurrent and asynchronous exchange of messages. The system is event-driven: it rapidly self-organizes to accommodate events that affect its operation.

Problem domain knowledge is elicited and represented as a semantic network where concepts (classes of objects) are nodes and relations between concepts are

links. Each object is characterised by attributes and rules guiding their behaviour. Such a conceptual knowledge repository is called Ontology.

A real-life problem situation is represented as a virtual network of instances of objects defined in Ontology and their relations. Such a problem description is called a Scene.

The elementary computational element is called Agent. An agent is a computer program capable of solving the problem at hand by consulting Ontology and using thus acquired knowledge to negotiate with other agents how to change the current Scene and turn it from the description of the problem into the description of a solution. Agents solve problems in co-operation and/or competition with other agents. As Events (new orders, failures, delays) affecting the problem domain occur, agents amend the current scene to accommodate the event thus achieving Adaptability.

An agent is assigned to each object participating in the problem-solving process (and represented in the scene) with a task of negotiating for its client (object) the best possible service conditions. For example, Passenger Agents and Seat Agents will negotiate take off/landing times and seat prices for requested air taxi flights. Closing a deal between a Passenger Agent and a Seat Agent indicates that a full, or at least partial, matching between Demand and an available Resource has been achieved. In case of a partial matching (*e.g.*, a passenger agrees to accept a later take off time but it is not pleased), his Agents may attempt to improve the deal if a new opportunity presents itself at a later stage (*e.g.*, if other passengers on the same flight agree an earlier take off time). The process continues if it is necessary to obtain full matches, or until the occurrence of the next desire event (say, a new request for a desire seat) which requires agents to re-consider previously agreed deals.

Agent negotiations are informed by domain knowledge from Ontology, which is far more comprehensive than “rules” found in conventional schedulers and normally includes expertise of practicing operators. Not all this knowledge is rigid - certain constraints and if-then-else rules may be considered as recommendations and not as instructions and agents may be allowed to evaluate their effectiveness and decide if they should be used. In some cases, agents send messages to users asking for approval to ignore ineffective rules or to stress nonessential constraints.

The power of agent-based problem solving is particularly evident when the problem contains a very large number of objects with a variety of different attributes; when there is a frequent occurrence of unpredictable events that affect the problem-solving process; and when criteria for matching demands to resources are complex (*e.g.*, balancing risk, profits and level of services, which

may differ for different participants).

As the process is incremental, a change of state of one agent may lead to changes of states of many other agents. As a result, at some unpredictable moment in time a spontaneous self-accelerated chain reaction of state changes may take place, and after a relatively short transient time the overall structure will switch its state practically completely. Once the resulting structure has settled, the incremental changes will continue.

Agent-based problem solving process appears to exhibit autonomy and intelligence, known as “emergent intelligence” and is therefore often called “intelligent problem solving process”.

7.1. Architecture

A multi-agent software comprises the following key components:

- i. Multi-Agent Engine, which provides runtime support for agents;
- ii. Virtual World, which is an environment where agents cooperate and compete as they construct and modify the current scene;
- iii. Ontology, which contains conceptual problem domain knowledge network; and
- iv. Interfaces.

7.2. How Multi-Agent Software Works

Software consists of a set of continuously functioning agents that may have contradictory or complimentary interests. Basic roles of agents, based on extended Contract Net protocol, are Demand and Supply roles: each agent is engaged in selling to other agents its services or buying services it needs (Passenger Agents buy seats and Seat Agents sell them).

Current problem solution (current scene) is represented as a set of relations between agents, which describe the current matching of services; for example, a schedule is a network of passengers, seats, aircrafts and flights and relations between them.

The arrival of a new event into the system is triggered by the occurrence of a change in the external world; for example, when a passenger requests a seat on a flight, a Seat Request Event is triggered in the system.

The agent representing the object affected by the new event undertakes to find all affected agents and notify them of the event and the consequences (*e.g.*, the agent of the failed aircraft undertakes to find Passenger Agents linked to the failed flight

and inform them that the flight is not available; the Aircraft Agent breaks the relevant relations and frees the Passenger Agents to look for other available flights.

The process of problem solving can run in parallel and asynchronously and, consequently, simultaneously by several active participants.

For example, passengers that arrived at the website to book a flight simultaneously can all immediately start searching for suitable seats. All aircrafts assigned to flights can start immediately looking for free pilots. This feature is very effective because it eliminates a laborious building of flight schedules only to find out that pilots are not available for all selected flights.

The driving force in decision-making is often the presence of conflicts, which should be exposed and settled by reconsidering previously agreed matches.

For example, if a new flight finds out that the take-off time slot it needs is already occupied, negotiations on conflict resolution start and, as a result, previously agreed flight-slot matches are adjusted (the take-off time slot is moved to accommodate both flights) or broken (the time slot is freed). This capability to make local adjustments before introducing big changes is what makes agents-based problem solving so much more powerful in comparison with object-oriented or procedure-based methods.

A multi-agent system is in a perpetual state of processing - either reacting to the arrival of new events or improving the quality of previously agreed matches. The stable solution, when there are no agents that can improve their states and there are no new events, is hardly ever reached (agents are perpetually operating "far from equilibrium").

Solutions developed using multi-agent software fall into the class of open, non-linear and dissipative systems. As the number of relations increases in the system, the level of complexity of the resulting network goes up and, at a certain point, the need may arise to appoint additional agents to represent certain self-contained parts of the network whose nodes are already represented by agents. The increased complexity of solution structures may result in the creation of loops and the system may find itself in a local optimum. To avoid being stuck in a local optimum, agents are from time to time given power to pro-actively seek alternative solutions. Attempts to avoid local minima are random (mutations).

Multi-agent systems can learn from experience as follows. Logs of agent negotiations are analysed with a view to discovering patterns linking individual agent decisions and successes/failures of the agent negotiation process. In future

negotiations patterns leading to failures are avoided.

The pattern discovery process is itself agent based. An agent is assigned to each data element with a task of searching for similar data elements to form clusters. An agent is assigned to each new cluster with a task to attracting data elements that meet cluster membership criteria. Finally, clusters are represented as “if-the-else rules”.

7.3. Organizational and Process Design Cases

Systems that have been designed under my supervision, or with my involvement, using the above principles are described in some detail in [8 - 13]. Advantages of adaptability in comparison with rigid systems, such as ERP (Enterprise Resource Planning), are described in a popular format in [14].

The list is substantial and includes real-time, adaptive multi-agent systems for: managing 10% of world tanker capacity for global crude oil transportation (in use); managing 2000 taxis and other service vehicles in London (in use); managing an extensive road logistic system across the UK (in use); managing social entitlements of citizens in a very large region (in use); managing distribution of rental cars across Europe for a major global car rental organization (successful trials; in the commissioning stage); managing a car manufacturing system (prototype); simulating virtual enterprises (prototype); managing document flow for a major insurance company (prototype); managing all business processes of a new aviation company (in the design stage); managing a catering supply chain (in the design stage).

To illustrate the power of agent-based adaptive systems let me outline complexity of the design problem that I am handling at present. The goal is to design an adaptive organization based on teamwork, and a supporting intelligent multi-agent management system, which will make autonomously all operational decisions (how much to charge a customer for a flight, which pilot, aircraft, ground staff will be assigned to which duty, *etc.*) and manage domain knowledge required for strategic decisions (on expansion, on market penetration, on increasing business value) for a brand-new enterprise. The enterprise network will enable rapid interaction of twelve multi-agent modules, including simulators, several schedulers, a demand forecasting system, a human resource management system, and customer relations management system, and will maintain integrity of all enterprise data and several enterprise ontologies. The system is being designed to handle 4,000 travel requests a day, to book 400 taxi seats/flights a day and to schedule or re-schedule a large fleet of small aircraft, flights, crews, ground staff, aircraft maintenance, fuel supply, *etc* every 7 seconds, which is a task which would be impossible to achieve without agent-based technology.

7.4. Engineering Design Cases

I am not aware of any fully adaptive products in operation. However, I have researched, simulated or prototyped a few distributed, adaptive products following the design principles outlined above, including: a machine tool; an intelligent geometry compressor, an autonomous parcel distribution system and an intelligent family of robots [15, 16].

Perhaps the boldest idea is to design a compressor with moving individual vanes capable of autonomously and dynamically positioning themselves at the optimum angle whenever the operating point of the compressor changes. A software agent is assigned to each moving vane equipped with a pressure sensor. As pressure on the vane changes, the Vane Agent negotiates with agents of other vanes how to change vane angles to achieve the optimum pressure distribution along the stator. Before deciding, agents consult domain knowledge stored in individual agents' minds, which can be updated without interrupting work of agents, to fine tune compressor operation. A very successful simulation [17] showed that the compressor with autonomous vanes, when coupled with an aircraft jet engine, is fully adaptive to sudden changes of loads and can prevent stalling of jets caused by lack of air intake.

Replacing a robot by a family of smaller robots illustrates the advantages of designing complexity into artefacts even better. To avoid disasters that ruined both American and British Mars exploration robots (the first died from the accumulation of space dust on its solar cells after a week in space, and the latter fell into a crevice on landing and was immediately lost), I proposed to design a family of five smaller robots capable of cleaning each other, rescuing members of the family from disasters and, more importantly, able to complete their task successfully even if one or two of the family members were disabled.

A family of robots is an adaptive distributed system, which incorporates all critical complexity features listed earlier in this paper. All decisions are executed after a process of consultation and negotiation among members of the family. There is no "senior" robot ordering others what to do. Each robot is controlled by a set of interacting swarms of agents. Agents consult domain knowledge before making decisions. A copy of domain knowledge is stored in each robot's ontology, making it capable of undertaking any task within domain boundaries. The family represents a "swarm of interacting swarms" of agents and therefore exhibits a considerable emergent intelligence. Robots are trained to help each other, share the workload and self-organize the team if a member is disabled without losing ability to achieve the goal.

CONCLUSIONS

A comparison between adaptation in nature and in social systems helped the author to develop a set of principles for designing real-time, adaptive organizations, processes and products. Experimenting with very-large-scale multi-agent software systems corroborated proposed design principles. These principles appear to be counter intuitive – they support the creation of complex adaptive systems instead of, currently favoured, rigid predictable structures. The acceptance of this approach requires a complete change of the designer's mindset, which can be achieved only by extensive re-education. Principles have been tested in commercial projects and found very effective in domains characterised by frequent changes of operating conditions.

CONSENT FOR PUBLICATION

Not applicable.

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CONFLICT OF INTEREST

The author confirms that this chapter contents have no conflict of interest.

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CHAPTER 4

Without Inner Walls: A Concept of the Café's House

Theófilo Barreto Moreira Oliveira^{1,*} and Ulisses Targino Bezerra²

¹ Federal University of Paraíba, Campus Mamanguape, João Pessoa-PB, Brazil

² Federal Institute of Paraíba, Civil Construction, João Pessoa-PB, Brazil

Abstract: The present study aims to present a new concept and, possibly, a new trend in the context of architecture, called Concrete Nullification in Architecture and is based on the philosophical reflections of the French philosopher Jean Paul Sartre. On the basis of certain bio-inspiration and bio-design assumptions, it presents an actual building, located in the city of Brasília - DF, Brazil, comprising the concepts of Emptiness and Nullification. Its layout and interior dimensioning were designed with an absence of walls or internal physical divisions. This new housing concept is called OW (*Ohne Innerwände*) aiming through the construction process at a better disposition and reflection of contemporary living, which maximizes space utilization, improve light capture, ventilation, ergonomics, accessibility and acoustics. In this proposal, the interdisciplinary nature of knowledge is used to form a root-like network of architecture, anthropology, and philosophy which enables flow in the description and implementation of the proposed house, beginning with an explanation of the philosophical concept of nullification as developed by Sartre.

Keywords: Bio-inspiration, bio-design, without inner walls, OW, architecture, nullification.

“It was a very funny house,
(...) it didn't have anything.
Nobody could sleep even in a hammock,
since the house had no walls.
(...) But it had been built with great dedication”.
Vinicius de Moraes and Toquinho - The House

1. INTRODUCTION

Thinking of a house along the lines of the Vinicius de Moraes¹ [1] song can

* Corresponding author Theófilo Barreto Moreira Oliveira: Federal University of Paraíba, Campus Mamanguape, Brussels, Belgium; Tel/Fax: +5583988972703; E-mails: theofilo@gmail.com.br

practically lead us along three lines:

- i. an abstract and ideal house in accordance with the plain of Platonic² [2] ideas;
- ii. a ruin of some ancient civilization of which only fragments have remained through time to tell us its story; or
- iii. a sophisticated home, planned and architected as “creeping” from the vacuum; from nullification³ [3].

Of these three lines, we personally think of following the third proposal. After all, reflection concerning the issues of bio-inspiration and bio-design, and starting from a concept which presupposes the vacuum, or better, nullification, has led us to choose this somewhat anthropological⁴ and philosophical [4] investigation of contemporary architecture in the 21st century.

Thus, we present this reflective and *multi-natured* report of how we learned of this house, here defined as OW - Ohne Innerwände, which means, without internal walls.

When we first learned of the OW house, it was from another architect, Sidartha Razeira, a friend who works at IPHAN in Olinda-PE, Brazil, in one of his usual home visits to Recife-PE. We were discussing the viable and formal aspects of another study, also based on architecture, and that, at that time, had still not taken form. In late nights we debated the investigation under the influence of gourmet appetizers and other music, and in the same year of 2017, publication of a book, *The Strange Rio Tinto: traces of an enchanted story*, was successfully completed with the collaboration of Andréza Santos and Marlon Nilton [5].

While pursuing methodological hypotheses and speculations, and while trying to delineate housing divisions in Rio Tinto-PB, we were suddenly interrupted by a cellphone SMS to my friend Sidartha. He quickly relayed the message, laughed and said, “It’s my “brother” from Brasília - Distrito Federal”. “They call him “Café”. By the way, you need to see his house”. Immediately we asked, “Why?” He answered, “He designed it in a way ... you need to see it”! The evening went forward, and discussing my research continued normally.

After a few months, we personally met this Café⁵, who was now in Recife on other artistic work. We became friends, and we had the opportunity to see his house in Brasília when we were returning from a Philosophy Congress in Buenos Aires, Argentina. I was resolving some formal issues with the printer and publisher of my book. So, why not stay in the now “famous” house of Café?

Before arriving at his house, while still in Recife, Café contextualized the implementation of his home; the history of the land, an inheritance gift from his

grandmother, and the creative processes involved. In particular, he had used both bio-inspiration and bio-design, because the principal matrix of the house structure dates back to a pre-Socratic concept of nature developed by Anaximander of Miletus; *ápeiron* (ἄπειρον) *i.e.* a reality without boundaries, without limits, indeterminate, empty.

Thus, the process of creating the house, according to Café, started from three objective points arising from an inheritance constituted in a family heritage materialized in an old house, which fostered the following structure:

- i. First idea: sketching, planning and personal investment;
- ii. Second idea: demolition, the land and emptiness; and
- iii. Third idea: a house without internal walls.

Even under the influence of various architectural styles, the OW house does not strictly conform to any particular style. From the initial moment, though Café was inspired by the concepts of *Bauhaus*, Japanese homes, academic programs and architectural patterns, and bold contemporary designers with touches of ecological disposition, his home escapes any single style, but it inaugurates a new style and possibly a new trend. Initial questioners might well contest our view of OW as inaugurating a new style and a new trend. However, we directly reply, this house brings a new look to Brazilian architecture, and to the world.

In the end, conceptual breaks from any areas of knowledge are only possible from the moment in which we use the knowledge of the canonical; and giving way to new reflections to implode. Thus, we continue the investigation, in a virtual tour of this home, to understand how the environments were allocated and arranged without internal walls.

2. OW: WITHOUT INNER WALLS

Without discussing the entire history of architecture dating back to a classical discussion of what constitutes a house, or mark all of the influences that have arisen in the world, we will begin with a simple but complex idea. How does one think of a house and in its internal spaces from emptiness or nullification? How to think of this house without internal walls?

We are not discussing lofts. We are discussing fine grain thinking concerning the constitution of a house, with internal spaces, but without necessarily having walls between them. Logically, it cannot be completely without limits, or much less, a house in which the furniture will be providing divisions. A setting without walls in certain places could be detrimental to its own harmony. Upon reading this exposition, note the following detail: the walls of the house are external and not

internal.

Situated in an excellent location in Brasilia, Via W3, South Wing, the Pilot Plain; externally his home deceives all who see it. Extremely discreet to the inattentive eyes of pedestrians and passers-by in cars, in its interior, the OW guards a great reflective, artistic and architectural process.

With its walls having cast iron grade openings, the construction reveals (and conceals at the same time) a small and ornate garden, whose automatic entrance gate, remains integrated with metallic walls. Simultaneously, in a dialectical game of hide and seek, the house is completely revealed. Just pay attention. After all, who would say that a rectangular construction in a single block, with no apparent beauty, would keep a great architectural manifesto secret?

There is even a discreet concrete mannequin arm on the outside wall of the house, which goes unnoticed by those who have no patience and no time to appreciate the beauty of the simple things that present themselves around them (Fig. 1).



Fig. (1). External views: see the aspect of a simple box.

When entering the inner courtyard of the grounds, yet still outside of the house, a simple, thick, yellow door received us. Its color, despite being strong and alive, egg yolk yellow, has at its side, indicating the doorbell, a small graffiti of a tigress in human form.

Before entering the home it is important to emphasize that the climate in Brasilia is hot and dry for the greater part of the year, with an average temperature of 21°C, the summertime can reach up to 28°C. Imaginably, it is pleasant, although the data may be challenged with current climactic changes presenting lower temperatures during winter, to 12°C and in the summer to a maximum of 30°C. If it were not for the low pluviometric index, you could say that the climate is almost perfect. With the exception of the periods of intense rain, living in the Brazilian Northeast one can almost boast of having summer for the whole year.

The heat in Brasilia though is difficult, even for us. Therefore, we have only one observation: house interiors must support such climatic variations, leaving the internal environment always comfortable and pleasant. And this only happens if during the process constituting any construction, we think of such varied factors.

Upon opening the door and taking only two steps within, a climate shock occurs: the interior of the house is extremely pleasant and invigorating. The feeling is the same as being in a room with the air conditioning on.

What surprises is the size, giving the certain conclusion that the house has been carefully planned.

3. FLOOR PLAN

After a quick acclimation, yet without having investigated the interior of the house, we were surprised by the view. It is possible to simply see the four floors inside the house, without giving a step further. Tilting the head 15° downward (Fig. 2), we see the underground floor which is for his studio work. Returning to our initial position and tilting 15° upwards, we see a modern and sleek dining room, integrated with an American kitchen, in the most fashionable and current standards that you might imagine.

Raise my sight to 45°, and we come to the floor for the rooms and an access door to the pavement outside.

Imagining that there was a need to take advantage of all the built space, we discovered that this access door, would lead us to an area in the rooftop terrace with a breathtaking 360° panoramic view of the whole city (Fig. 3).



Fig. (2). The initial view of the room and its dependencies.



Fig. (3). Panoramic peripheral view.

But how can one better understand all of this visualization? How was the floor plan of the house conceived?

The land plot obeys the definition of condominiums, *i.e.*, the neighboring house has the same structure integrated with the former house on the land on which the OW house was built. However, since the OW house no longer has the same structure as its twin, we would say that the twin that constitutes a part of the OW house suffered.

During the creation process, Café informed us that he did not use anything from the old structure of the house. This generated a great implementation cost during construction, because even the old foundations were discarded. The implementation process needed to be meticulously observed so as not to compromise its nearby twin.

In this way, knowing that the area to perform the work of construction was restricted, the OW house used the land to the maximum extent and today it constitutes 217.60 m² of built area (Fig. 4). On account of its twin constitution, the internal construction usage planning was much more than necessary. The internal gains during construction, by removing the interior walls is a fundamental basis of this new housing concept, and offers a new perspective on internal divisions in a house; the objective is to best use the areas.

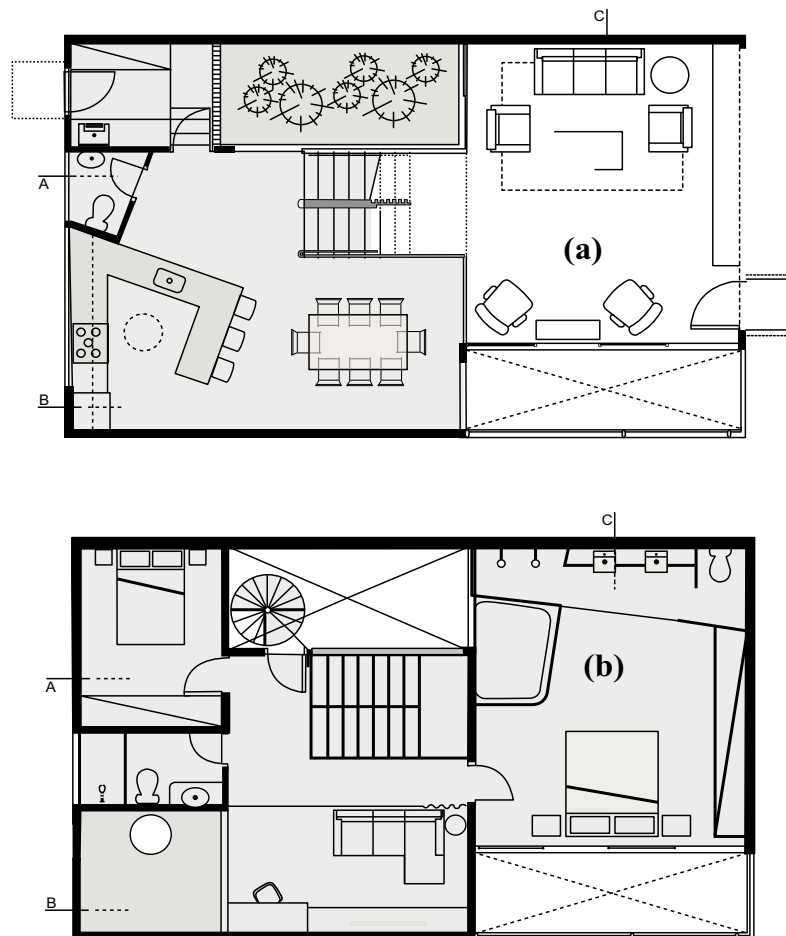


Fig. (4). Floor plan: (a) ground floor plan; (b) top floor plan.

As with this central idea, the other necessary criteria involve innovative architectural reflections that multiply in the form of benefits. Accessibility, ergonomics, furniture layout (decoration/design), lighting, acoustics and ventilation become harmonic elements of a great equation.

In accordance with the floor plan of the project, the house is divided into three levels: basement, ground floor, and upper floor. Each of these three levels contains a built area that today would be equivalent to four small 50.00 m² apartments. The basement/subsoil presents 67.95 m², the ground floor: 80.98 m² and the upper floor: 68.67 m². There is also a rooftop terrace with 80.00 m².

The technique used to gain a large space without the need of walls was through raising the environments yet while keeping them integrated, *i.e.*, instead of being able to raise a wall to mark the division of the house, the internal environments were highlighted so as to mark internal divisions (Fig. 5). Thus, space was gained for accessibility, ergonomics, lighting, acoustics and ventilation. Obviously, each one of these factors was quantified and prepared for both before and during the implementation of the building.



Fig. (5). Slices demarcating the environment: (a) longitudinal slice; (b) transversal slice.

Since the technical principle of the OW house is its constitution without internal walls through elevation of its environments, if one attempted to transpose this technique to the construction of small houses, or even to a set of small apartments, there would be an internal gain in space, providing greater convenience to its users. In relation to the criteria of accessibility, the internal movement of users

with locomotive difficulties would be facilitated. All of this must be planned for in advance, such that during the adoption of this technique, for each need there is a specific project, thus to completion.

To illustrate one of the above examples, see for yourself the illumination results (Fig. 6).

The objective was to make the most of the natural lighting so that throughout the house the light of the sun penetrates, economizing on the use of artificial light. Thus, one can think of having a more focused artificial lighting without direct or centralized lights, but with individual, discreet lights. Another example, that we can draw attention to is the acoustics. Styrofoam plates were placed between the walls of the OW house and its twin. In addition to reducing sounds and noises between the houses, they serve as thermal insulation, which enables the internal environment to be cooler and more pleasant in relation to the external environment.



Fig. (6). Natural lighting allowed by the absence of walls.

4. STUDIO

Starting the house visit, you start down the stairs and through Café's work studio (Fig. 7). The area, 67.95 m² as noted previously, is characterized by a large space divided in two, separated only by the staircase which marks the division between the spaces.

The first part of the studio has a large living room, illuminated by a horizontal channel, with a thin closed window from end to end, allowing sun light to come in. In this environment there is lighting practically throughout the whole day, the lighting is not excessive in terms of economy and convenience.

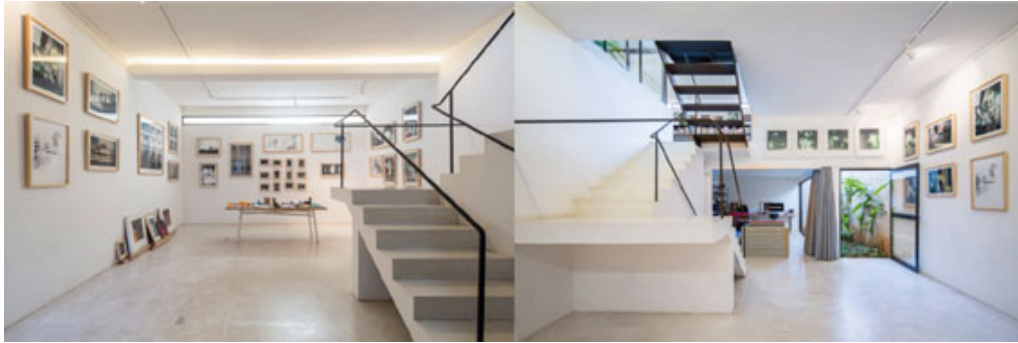


Fig. (7). Spot and diffuse lighting in some places.

For not having partitions; the environment can be used in several ways. For Café's artistic and photo work it is an excellent photography studio, and it can be freely transformed according to the creative processes with which he is working.

Further on one reaches the second area of the studio. It enjoys another source of natural lighting (Fig. 8); facing the previous area and alongside of this second studio area, there is a small winter garden which rises up to the rooftop terrace, giving space for both illumination and proper ventilation.

As in the upper part of the winter garden there is a large perforated steel plate which allows entry of both ventilation and lighting, the site remains reserved, always fresh and airy. There is a small bathroom underneath the staircase, making the area more harmonious and making the most of the available space. Working in two different environments in the same area, connected, yet without the obstruction of walls, yields maximum space utilization.



Fig. (8). External light penetrating the surroundings.

5. LIVING ROOM

Returning to the living room, comfort and coziness are provided by another

opening in the front wall of the residence, which contains another thin and horizontal window from end to end, allowing for a differing lighting perspective for the space (Fig. 9). Even with its large windows that provide a broad vision of the external environment, the view remains discreet on account of a perforated steel plate, which rises from its base on the ground to the base of the rooftop terrace. Freely out laid and with access to the second winter garden, the living room is the main access, with 30.55 m², which favors both its disposition, as well as its connections with all other environments. Its right side is 3.58 m high, extending the environment and yielding a sensation of grandeur, a break from what is usually presented in today's houses and apartments.



Fig. (9). Lighting by means of a longitudinal opening.

6. KITCHEN AND DINING ROOM

At its best contemporary style, the kitchen itself shines in harmony with the dining room (Fig. 10). The trapezoidal American bar features recessed cabinet pulls, elevating the design environment by breaking with traditional opening knobs and handles. The dimensioning, although asymmetric to the rectangular layout of the entire construction, presents an almost rare beauty that balances its forms.

The cabinets opposite the bar traverse the invisible extension of this area, highlighting provision for wide internal movement within the space. Complementing the kitchen's extension, the lighting is composed of horizontal windows and a skylight that maintains the bright and cozy environment.



Fig. (10). View of the Kitchen being demarcated by the furniture.

The dining room is double purpose. Folded away towards the opposite side of the bar, it presents a comfortable, large and airy space whose front window presents a suspended bar top, with a view to the winter garden, present in the sub terrain.

The dining room's side view also receives natural lighting from the second winter garden present in the house, as integrated with the living room area the lighting is almost 360°.

7. OFFICE AND BALCONY

In the best style of free disposition, *i.e.*, without barriers or screens that divide administrative professional environments, and escaping even the classical style of the formal office surrounding in books, armchairs, and bureaus which divide the workspace into two or more parts, the office offers a cozy space to do business in the best contemporary style yet without a purely commercial appearance.

It flees the hermetically sealed aesthetics, so to speak, of a common office. Fully illuminated by a window that gives access to the winter garden of the subsoil of one side, it features a small terrace in conjunction to its space, which further justifies the entry of natural lighting without consumption of surplus energy (Fig. 11).

A mixed environment, linking two distinct spheres, yet which may connect mutual interests, aggregating the formal and informal, or better said, personal interests and professional interests, the working environment of the house provides both users, a great place for business and study, with the possibility of an afterhours *happy hour*, enjoying a well aerated view from the outside terrace.

Not to mention the existing interaction between the skylight view and the kitchen below, the polyphonic environment⁶ [6] accommodates multiple discussions and

functions between environments above the office, the rooms, the WC and the rooftop terrace.



Fig. (11). Office demarcated by the floor.

8. BATHROOM/WC

Recalling old and spacious bathrooms, but with ecological capturing of solar energy for heating the water, the bathroom (Fig. 12) is presented with cool and comfortable tones, literally providing the pleasure of diving into the open sea, because it is coated with blue tile that simulates the clear waters of a tropical ocean. Its strategic positioning integrates all cooler parts of the house, being allocated above the lavatory, which is next to the kitchen, and almost imperceptible to the service area, once again taking advantage of the natural light and with large windows which also provide good ventilation.



Fig. (12). Toilet with walls for obvious reasons: an exception!

9. LAVATORY

In the same way that nature offers unexpected solutions to the sphere of life, the lavatory (Fig. 13) which exists in this house was created only to facilitate access to rapid passages of its users in the house. Trapezoidal shape optimizes a small space which occurs between the kitchen's limits established by cabinets, and the service area. Simple and in slightly darker colors, it fulfills its objective functionality.

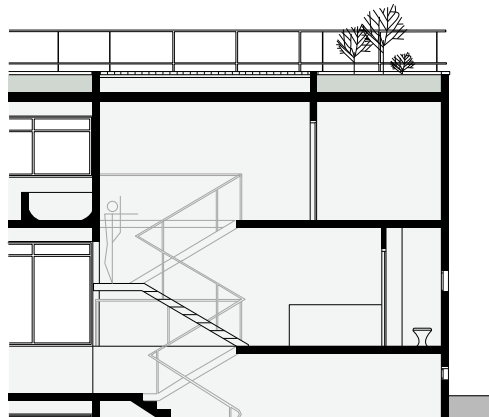


Fig. (13). Lavatory.

10. GUEST ROOM

Basic, spacious, airy and bright: the guest room (Fig. 14), to speak of more than these in a provision of approximately 10 m², would not comply with the principle of emptiness that governs the house.

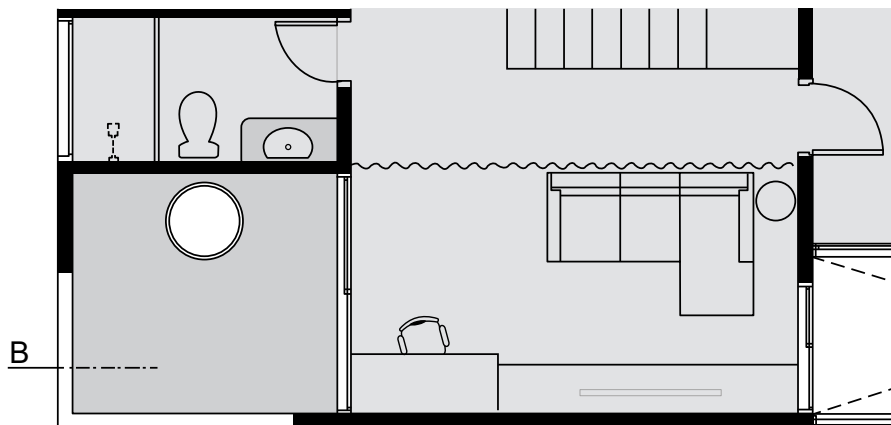


Fig. (14). Guest Room.

11. SUITE

Fleeing from all logic of a suite, it could be very well presented as a relaxation *playground* offering approximately 30 m² of internal space, two sinks, two showers, a sanitary bowl and a bath (Fig. 15). Through a game of hide and seek it manages to maintain an open equilibrium, having visual breaks in its environment, which do not reveal everything, and yet at the same time do. The division of spaces reveals the commodities of the room without the use of walls.



Fig. (15). Suite.

12. ROOFTOP TERRACE

The rooftop terrace (Fig. 16) is 80 m² of free area with a 360° panoramic view towards the *Asa Sul* (southern area of Brasilia). It is located above the second winter garden and its entrance neighbors the superior office space. Access is by a helical metal ladder (Fig. 17) which is located between the two rooms. The rooftop terrace features a small garden, a comforting shower to cool off on hot dry days in Brasilia, and a 750 liter water storage container coupled to solar panels which provide heat for the shower water.



Fig. (16). Rooftop terrace.



Fig. (17). Helical metal ladder.

13. SERVICE AREA

Hermetically sealed walls, composing a space of approximately 5.24 m², confirming an enclosed quadrilateral from walls existing in this house?

Impossible, since the delimitation that exists in blueprint is breeze blocks, hollow elements which border the winter garden in the service area and allowing two factors in the OW house: (i) natural lighting, and (ii) ventilation. The option of using breeze blocks may have been a decision in aesthetics alone. After all, according to Brazilian engineering and architecture law, the notation marked in the blueprints as a hollow element is not the same as delineating a wall. If it were, the graphics would be the same.

14. THE NULLIFICATION OF OW

The presence of an absence?

The absence of a presence?

Nullification during the concreteness of human actions?

How to uncover the real?

Gottlieb Olivenbaum

It is in the words of an unknown thinker, of which we have only very few reports or almost nothing, that begins a brief reflection concerning which bio-inspiration and bio-design aspects exist in OW. The presence of an absence? The absence of a presence? Nullification during the concreteness of human actions? What do these mean?

A debate concerning the aesthetics of absence, parts from a principle which is completely antagonistic to objective and concrete reality. Having been conducted by the sciences of Engineering, Architecture and Design, at first glance this discussion becomes very strange, if not bordering on the ridiculous.

Mainly because, the presence of an absence, and the absence of a presence, and nullification are concepts present in other philosophies, such as Walter Benjamin and Jean Paul Sartre [7 - 11]. However, what draws attention to this quote from this obscure contemporary thinker, from the region of *Saarland*, is the joining of concepts having the aura of Benjamin with the nullification of being of Sartre, as a constitutional structure of his own being, *i.e.*, for there exists so much to be, it is necessary that this brings nothing, as an objective phenomenon of the intellect, so that, at the moment in which the question about being or lack of it (non-being) is proposed, one automatically devises a real and concrete understanding of the world, resulting in one's own nullification.

Based on the analysis developed and described throughout this article, in an innovative, iconoclastic, but also free manner, one of the main factors that

corroborate the terminology of the presence of an absence and the absence of a presence is the nullification of walls in the structure of the house itself. Upon determining that the concept of OW is structured in an absence, it automatically brings to the fore its own determination, as Sartre affirms, following the thoughts of Edmund Husserl in his concept of intentionality, that “all consciousness is consciousness of something”.

Following this dialectic treadmill in which when questioned about the possibility of creating something from its own nullification, Café conceived the design of his OW. Having as a goal the nullification of concrete reality, proposing the question of the possibility of building a house without inner walls, he not only left the possibility of being, but brought to the fore the possibility of not-being. Because, as a proposition, he could have two responses: (i) the positive, which would claim being, and (ii) the negative, asserting the absence of this being, *i.e.*, the non-being of the house. As a result of this dialectic action, nullification while conscious of something became that which was not only possible, but real and concrete in human action, the OW house itself. After all, “[...] what being will be must necessarily cut into the background of what is not” [3].

Thus, the conceptual structure that OW presents is nothing more than the finding of a lack of concepts concerning it. By questioning the possibility of building a house without internal walls, modifying the internal allocations and expanding the use of space, Café presented not only to Brazil, but to the world, a new way of perceiving reality, from natural inspiration in its own emptiness, or in the words of Sartre, from nothing.

Thus, a new trend begins in the field of architecture, defined as “concrete nullification in architecture”, given that nullification is not annihilation or destruction, but actually accompanies the presentialization of being, and dismisses awareness conceived as something distinct from itself. Nullification in concrete architecture, as demonstrated in the structure of this house, brings new possibilities for thought about internal spaces within a building. And starting from an economically varied assumption, since replication of this technique may occur in smaller or larger environments, liberates the creativity of the architect, engineer or designer who takes ownership of this concept. If the current challenge is to return to equilibrium within nature, no longer trying to dominate it while excluding the equation of the universe, but to follow its guidance in structuring bio-inspiration and bio-design, then the entire structure presented by the OW house answers this call. The presence of an absence reveals the absence of a presence in this concrete nullification.

NOTES

¹ According to a paper published in Folha de São Paulo dated 19.10.2013, written by Juliana Ferreira, the house from which Vinicius de Moraes based the composition of this song, exists, and is found in Uruguay. It was developed by the artist Carlos Páez Vilaró.

² PLATÃO. The Republic - Book VII. 2nd Ed. Trad. Elza Moreira Marcelina. Brasília-DF: Editora UnB, 1996.

³ The term nullification is one of the main concepts of the philosophy of Jean Paul Sartre. Very simply, according to its etymology, to nullification means to reduce to nothingness. The concept is structured in making the being a phenomenon of itself, since it is also treated as an object by the conscience. Here it is important to state also that nullification is not the same thing as annihilation. This second concept aims at destruction.

⁴ When we express the anthropological term here, we think of two positions: First in the ethnographic method as philosophical reflection, in accordance with Michel Foucault and Eduardo Viveiros de Castro, and secondly, when visiting and getting to know this building in Brasília, we think of completed field research, which has generated the reflections presented in this article.

⁵ Carlos Café is a professor of architecture at Unieuro University, architect and photographer. He develops artistic works with various types of media.

⁶ The term polyphonic is presented by Massimo Canevacci in his work, The Polyphonic City, in which this Italian anthropologist presents the multiple lines that exist in a fully multi-natural environment of a city with varied voices.

CONSENT FOR PUBLICATION

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CONFLICT OF INTEREST

The authors confirm that this chapter contents have no conflict of interest.

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CHAPTER 5

Similarity Between Particle Packing in Concrete and in Nature

Eng. Piet Stroeven^{1,*} and Eng. Kai Li²

¹ *Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands*

² *College of Civil Engineering, Hunan University, Hunan Sheng, China*

Abstract: This chapter deals with the issues related to packing of particles in nature – aggregate in the first place - and in cementitious materials. Many of these topics are extensively discussed in the international literature, so will only be briefly introduced, while additionally giving a restricted number of references. Relatively new developments, such as producing the realcrete by computer, yielding compucrete, will receive more explicit attention. The way to do this properly by DEM (discrete element method) instead of by popular RSA (random sequential addition) is stressed. Modern dynamic DEM renders possible simulating aggregate of fluvial origin as well as of crushed rock. Similarity of simulating particle packing on mesolevel (aggregate) and on microlevel (binder) was the argument to sketch modern developments in the latter field, because they provide information on permeability and are thus of paramount important for sustainability. A phenomenon recently receiving attention in the literature is Brazil Nut Effect. It is a part of nature and it can significantly influence the compacted particle structure of aggregate or binder alike. Some relevant information as to cementitious materials will be provided.

Keywords: Aggregate, binder, concrete, discrete element method, particle packing.

1. INTRODUCTION

Nature provides the mechanisms for particle packing we are interested in. However, we only observe the result such as revealed by Fig. (1) for packed aggregate in a river bed. Hence, we have to unravel the processes that have led to such final results.

As to applications for concrete technology, we are interested in getting the aggregate into its densest packing. This will reduce the amount of the binder, so is

* **Corresponding author Piet Stroeven:** Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands; Tel: 0031(0)152784035; E-mails: pieter37@xs4all.nl

of economic interest. However, since the production of the cement also involves the emission of large quantities of CO₂, it would also be of ecological interest. Further, the aggregate of fluvial origin and of crushed rock alike, will provide the concrete with a (compressive) load-bearing skeleton. Finally, less cement also means smaller amount of pores, which should promote durability and sustainability alike. Research has shown this to be less obvious, however; a topic we will touch upon later.



Fig. (1). Packed gravel in river bed. Larger grains lay on top of the smaller ones.

The most obvious conclusion from observations in nature seems that when pursuing the densest packing of aggregate, compaction by vibration should be undertaken. Mix design is also appealing to experiences in nature: a range of sizes can be packed more densely than in the case of mono-size particles. And this is traditionally the standard procedure in concrete engineering, either dealing with onsite concrete or precast element production. Relatively modern developments like self-compacting concrete (SCC) can nevertheless do without compaction. It should be noted here however that the “simple” mix design and production technology are more or less taken over by chemistry in the modern concrete technology developments, such as with SCC. All sorts of chemical admixtures provide the fresh, hardening and matured concrete with properties required by the specific application demands for the very concrete. The intimacy of the state of the aggregate in nature and in the concrete is thereby somewhat camouflaged. Yet, most of the concretes used today are still of normal quality (or eventually of high strength quality), produced according to standardized procedures and principles, whereby compaction by vibration is exploited to get the aggregate under given

circumstances into the densest packing without the occurrence of segregation.

The difference between normal concrete and (super) high strength/performance qualities is that density is promoted in the latter cases by paying special attention to mixture design – particularly based on gap-graded ranges of particle fractions. In discussing modern material developments in the super high performance range and with respect to engineered cementitious composites, it is therefore concluded that “the optimum packing of particle ranges and fibres is an integral element of this performance-driven design approach in the field of concrete technology as far as special concretes are at issue” [1]. But also surface conditions (particles of fluvial origin or of crushed rock) play a role. Traditionally, optimization is achieved on the basis of extensive experimental testing. The involved efforts can be significantly reduced nowadays by doing this in virtual reality. We will pay attention to these relatively new developments in a forthcoming section.

A phenomenon that should be mentioned when discussing aggregate packing is the “boundary effect”. It occurs in nature as well as in man-made concrete. The optimum particle dispersion that could eventually be realized in bulk is disturbed by nearby rigid surfaces such as by the formwork and steel bars. Specifically, grains are pushed away from such obstacles depending on their respective sizes (*i.e.*, to at least a distance equal to half its “diameter” [2, 3]). This results in a local composition of the aggregate mixture different from that in bulk; a so called gradient structure is formed, whereby average grain size of the mixture diminishes upon approach of the rigid surface. In parallel, also volume content of aggregate is reduced. So, cement content is largely closer to external surfaces, causing the boundary zone to be more liable to shrinkage cracking. Among the measures to reduce this risk, randomly dispersed fibres are used. This is not a new appropriate technology, since its roots go at least back to the Pharaohs period in Egypt. However, it is still being practiced in Africa and by American Indians in the form of straw reinforced mud. Under the pressure of sustainability, vegetable fibres of a wide variety are also applied nowadays in cementitious materials, particularly for low cost housing purposes [4 - 6]. Their stability in cementitious materials is however still a problem, unless applied for indoor applications in reinforced concrete or in building blocks, of course. And in arid climates (as in the aforementioned settings) there is the durability of the cementitious fibre-reinforced composite of a proper level.

Packing of particles of a wide range of sizes is a general phenomenon in the materials field. In concrete, it ranges from the meso-level down to the micro-one (with measures in cm to μm). Aggregate packing in cementitious materials is associated with the skeleton formation for resisting compressive loadings. Tensile stresses are traditionally designed to be transferred by steel reinforcement (and by

fibres). A vast literature in a range of disciplines is available on particle packing phenomena, as can be found on the Internet. Also international conferences attract many researchers and practitioners in an interdisciplinary setting, such as on the yearly organized ECCOMAS Thematic International Conference on Particle-Based Methods — Fundamentals and Applications in Barcelona, Spain. When focusing on concrete, we also have particle packing on a lower level of the microstructure. The fresh binder particles (cement, eventually blended with a mineral admixture) also have to pack in the watery environment. When the water to cement ratio is very low, as in (super) high performance concrete, the binder packing density can be as high as 60%, close to the loose random packing state. These particles have to pack in the limited space left by the packed aggregate that occupies (at least) three-quarters of the available volume. The average distance between nearby aggregate grain surfaces amounts to 50 μ m [7]. This is of the same order of magnitude as the thickness of the Interfacial Transition Zone (ITZ) in the hardened binder paste, which is primarily due to the “boundary effect” in the packed binder particles in the fresh state. Obviously, particle size distribution is a relevant parameter, further shape and surface roughness (some mineral admixtures are composed of spherical smooth-surfaced particles, whereas the cement grains have been shown rough-surface angular particles [8]) are important issues. Basically we deal with a similar packing phenomenon as with aggregate packing! Also in both cases, interesting features are the topology and geometric parameters of the space left after packing. In particular, in the case of binder particle packing, we are confronted here with pore space characteristics that are of utmost importance for durability.

Seeing the densities involved in particle packing of aggregate or binder, the dispersion of the particles cannot be “random”. In fact, we deal with a complicated state in which chaos and order compete. This makes the production of virtual materials complicated, since the ratio of the two states varies depending on the leading material parameters mentioned earlier. So, the strategy of producing virtual cementitious materials should be simulating a representative mixture under forces of vibration by compaction. The dynamic Discrete Element Method (DEM) offers such possibilities. The result is a compucrete approaching the realcrete as close as possible, given the computational possibilities. We will come back to this in a separate section.

2. REALCRETE AND COMPUCRETE

The aggregate grain structure on meso-level is in the compacted concrete of dense random nature, at a volumetric density of about 0.75, depending on the grain shape and on the sieve curve that crudely defines the grain size distribution function. Wall effects have been recognized for a long time due to the mold.

During the 90th of the previous century, the concurrent algorithm-based DEM system SPACE became available for producing realistic manifestations of cementitious systems. The only concession in the representation of reality was the use of spherical particles [9 - 11]. The system has been extensively applied for studies on meso-level (aggregate) [12 - 15]. However, the next step was an application to the binder structure on micro-level (blended cement). In the latter case, the focus was on the pore structure and on the paramount importance of the ITZ in the pore depercolation process accompanying the maturation of the material [15, 16]. Gradient structures of various parameters that are the inevitable result of wall effects were investigated, including total porosity and the fraction of connected porosity. Even total porosity was found slightly configuration-sensitive. Recently, the successor of SPACE (Fig. 2), the HADES system was also applied to both levels, whereby in the case of aggregate grains, shape effects were studied [2] and for (blended) cements, porosimetry was optimized [17]. Further, permeability estimation was made possible also for partially water saturated conditions of the concrete [18].

How do we do that, making virtual concrete? What characteristics of the complex, particulate material should be incorporated in this so-called *compucrete*? Such questions must have been at the minds of those coming up with the first systems in the 70s of the previous century, such as that of Roelfstra [19], which formed the starting point of the numerical concrete concept of Wittmann *et al* [20]. For a parallel development in our group, see He *et al* [11]. Basically, most developed systems in concrete technology rely on sequential random (particle) addition algorithms (RSA) [21 - 24], or completely randomized approaches [25]. In RSA systems, particles are placed proceeding from large to small on preconceived positions of a Poisson field. Violation of physical conditions by over-lap leads to rejection and re-generation. So, part of the Poisson field positions cannot be exploited, since spacing with other points is insufficient. The consequences are that new positions should be randomly assigned to remaining particles until overlap is avoided. This is a time-consuming process, whereby the number of re-generations dramatically increases when volume fraction is approaching a level of only slightly over 35% in mono-size packings. In [26] an upper limit of 38.5% for spherical particles is mentioned, which is in qualitative agreement with [27] where in most of the cases the production of virtual concrete with 40% spherical aggregate failed. So, practical arguments plea for application to low density grain mixtures only. Next, instead of having series of particles close together in the compucrete, in conformity with a Poisson point process, on average a more uniform dispersion is obtained, leading to significant spacing differences. Clustering, a natural phenomenon in particulate matter [28], is therefore very poorly represented by RSA systems.

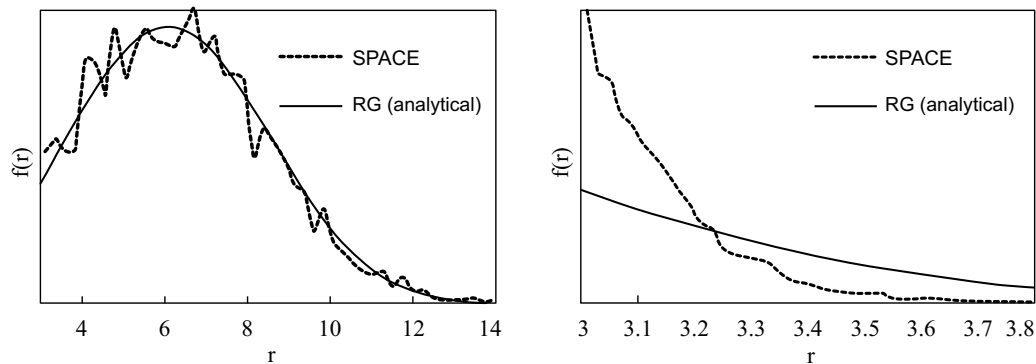


Fig. (2). Deviations between predictions on nearest neighbor density distributions, $f(r)$, at 1% (left) and 30% (right) by volume of aggregate obtained by random generator (RG), respectively, by concurrent algorithm based (SPACE) computer simulation systems [9].

Contrary, the concurrent algorithm-based DEM computer simulation system that will be introduced herein imitates the production conditions of concretes and has been demonstrated realistically revealing the clustering phenomenon [9, 10, 29]. See for additional information on DEM [30, 31].

Modeling pursues a schematization of reality with operational potentials. This already points to the intimate relationship between the type and degree of schematization and the objectives for making the appeal on the operational potentials. We don't have to schematize all aspects of the inherently complex system that concrete definitely is, but only those relevant for obtaining this unbiased 3D structure information on which the aspect of material performance relies we are interested in. A complicated task, anyhow. However, we might discover that at least some of our questions deal with the aspects of material performance that have a low structure-sensitive nature. Hence, the schematization of reality is not very demanding for the simulation system when the researcher is targeting material density, or volume fractions of composing compounds of the material. These are composition characteristics of the material. The associated material properties that completely depend on composition are denoted as structure-insensitive properties (like mass, or approximately, Young's modulus). When investigating particle spacing, or local grading characteristics, one is dealing with configuration characteristics of the material. The associated material properties are referred to as structure-sensitive properties. So, the schematization of reality is quite demanding for the simulation system when the researcher's focus is on structure-sensitive properties, like fracture characteristics. The compconcrete should be more sophisticated in such cases, because configuration of particles, the so-called group effect, will influence these properties.

Available physical discrete element computer simulation methods for forming granular packing of hard particles can be placed, therefore, in two distinctive groups [10, 11]. Most computer simulation systems in concrete technology fall in the first category. They generate granular packing of spheres or particles with other idealized shapes by random sequential addition, RSA. The second group, based on so-called concurrent algorithms, involves the densification of a fixed number of particles. This is generally attributed as discrete element methods (DEMs). The strategy to solve the overlap problem is either of static or of dynamic nature. In both cases, the container size is initially enlarged so that all particles can be positioned at the Poisson points. Thereupon, the container size is gradually reduced and the particulate system squashed. The mechanical contraction in [27] is a static solution, which involves local shifting of particle positions to eliminate overlap. The SPACE system that has been developed at Delft University of Technology realizes the compaction by a dynamic algorithm. The dynamic stage is supposed to imitate, moreover, the production stage of the material. The forces added to the particles can be manipulated, so that “sticky” particle contacts (or particle repulsion) during the production of the model material can be simulated. Also gravity effects can simply be included. SPACE is based on spherical particles only [9]. The newer Delft-produced DEM system denoted by HADES can encompass non-spherical particles [2]. Moreover, particle interaction is force-based instead of impulse-based as in SPACE. This is to account for particle shape effects that can have significant impact on packing and thus on mechanical and durability properties. Also experiments in which a granular mixture is subjected to external forces (to increase density) can be executed. Descriptions of the two DEM can be found in the open international literature [11, 32, 33].

The compucrete is produced in limited quantities in cubic molds. Basically, containers with rigid walls are used, or with so-called periodic boundaries. The first situation conforms to a molded aggregate, or to cement paste pocketed between surfaces of aggregate grains. The second type of boundary conditions is used to simulate bulk material (Fig. 2). Also mixed situations can be modeled. The production of virtual material is basically the same for aggregate or for binder particles. The latter would be necessary for investigating the effect of packing of binder particles in the fresh state on pore characteristics and thus on durability. Of course, in this case hydration should be additionally simulated.

3. AGGREGATE PACKING BY DEM

3.1. Bulk Packing

One of our first experiments was dealing with *river aggregate* (sand and gravel)

that was simulated by SPACE by about 1500 spherical particles. A series of six different sieve curves was considered of particles between 1 and 32 mm. The real aggregate mixtures were compacted by vibration in standard 8-liter cylinders [9, 10, 32]. Fig. (3) compares the experimental and SPACE-simulated ultimate densities of the mixtures. In both cases the trend is similar, with optimum packing somewhere between mixtures D and E. Mixture F is a so called equal volume fraction mixture, so containing a large amount of fine material. The Fuller mixture is between D and E. It is supposed to lead to optimum results in terms of packing density. The sieve curves underlying the experiments can be found in the aforementioned publications.

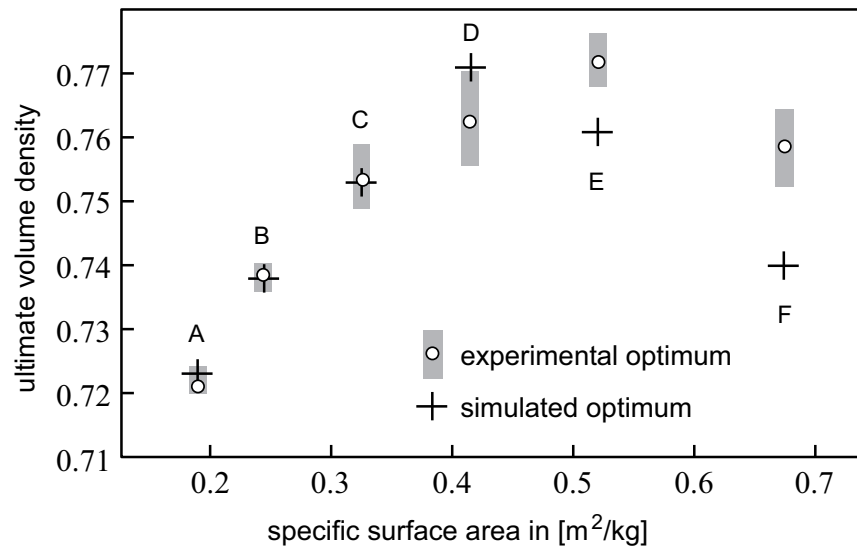


Fig. (3). Comparison of the density at the jammed states of different mixtures of river gravel aggregate compacted in standard cylinders, and of SPACE-generated spherical aggregates with similar grading characteristics (correspondence is satisfactory) (mixtures A to E have increasing density).

An extensive *experimental* program to aggregate packing in concrete performed by the first author in the early 70th of the last century has been widely reported on. In a traditional concrete mixture, the largest sieve fraction of gravel was replaced by a 16 mm ceramic mono-size aggregate of spherical shape and representing average size in this removed aggregate fraction. At the same total amount of aggregate, three different amounts of ceramic aggregate were investigated. Since water to cement ratio was kept constant, workability was different for the three mixtures and the compaction by vibration period was therefore also adapted to guarantee proper compaction. Results can be found in [34]. One of the interesting aspects investigated forty years later was whether we were able simulating such mixtures by dynamic DEM. Fig. (4) shows the validation by a tough test, namely

the highly structure-sensitive nearest neighbor distribution measured in the realcrete and obtained in the compucrete. The differences in the two distribution curves are primarily due to inaccuracies in the measuring of the nearest neighbor in the experiments. For that purpose, the 250 mm cubes had their surface layer removed so that 200 mm cubes were resulting. Next these cubes were serially sectioned by sawing the cubes into 11 mm thick tiles. This implied all ceramic grains to be visible in (at least) two successive sections of which one is presented as an example in Fig. (4). Three coordinates were recorded per grain in the section plane on a measuring tablet, which rendered possible the 3D reconstruction of the full structure of the ceramic balls.

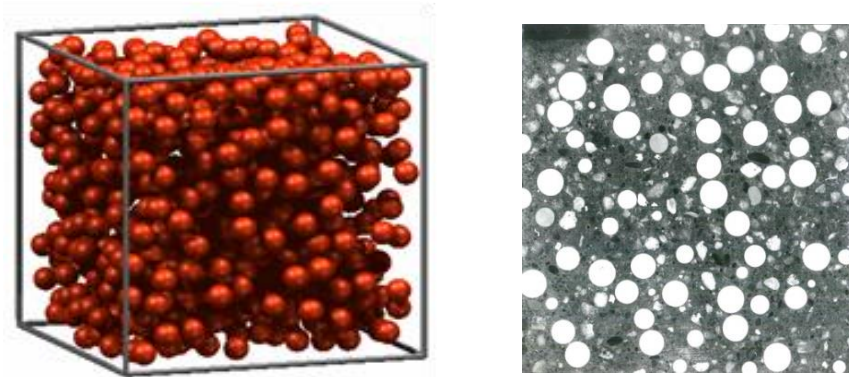
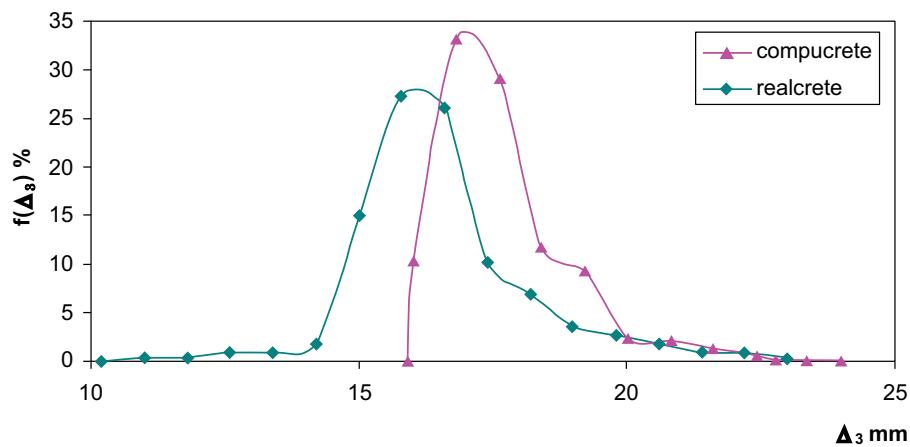


Fig. (4). Top: frequency distributions of the nearest neighbor, Δ_3 , among 16 mm ceramic spheres in a 200 mm sample; bottom left: compucrete; bottom right: realcrete.

The shape of individual particles can be assessed in different ways [11, 12]. In HADES, the particles can be of arbitrary shape, however, for economic reasons

similar families of shapes are selected. Fig. (5) shows a possible set up for simulation of river gravel aggregate (ellipsoids) and for crushed rock aggregate (polyhedrons). Fig. (6) presents by HADES simulated loose random mono-size packing states of different polyhedron types. Of course, the real aggregate has to be analyzed as to a particular shape parameter, such as sphericity. This is defined as the surface area ratio of the equivalent sphere and the relevant particle, whereby sphere and particle have the same volume. The obvious influence of the sphericity of the selected polyhedron (in a wider range than depicted by Fig. 6) on packing density is shown in Fig. (7). In the presented situation, the loose random state was simulated, however the mixtures were additionally compacted into the dense random state, whereby basically similar shape effects were found [2]. The observed shape effect is confirmed by experimental data in the literature [35].

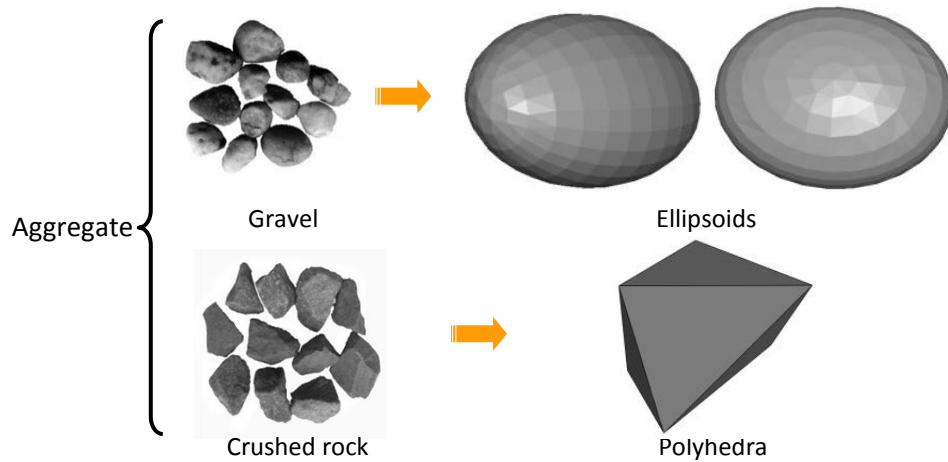


Fig. (5). Strategy of simulating different aggregate types in numerical concrete.

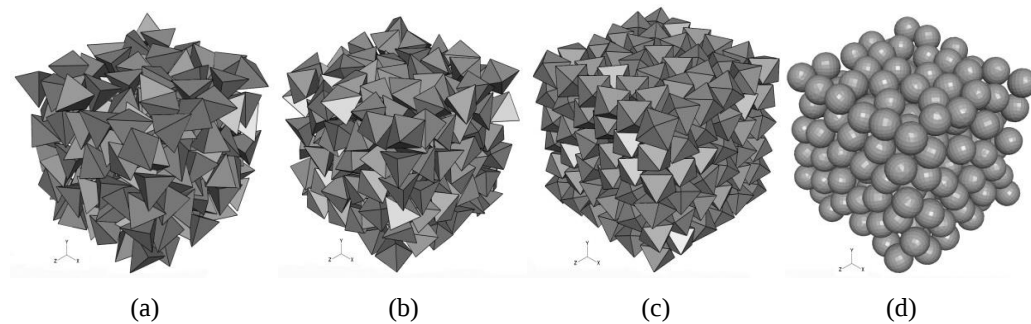


Fig. (6). Mono-sized random packing with particles having typical shapes: (a) tetrahedron (b) hexahedron (c) octahedron and (d) sphere, respectively.

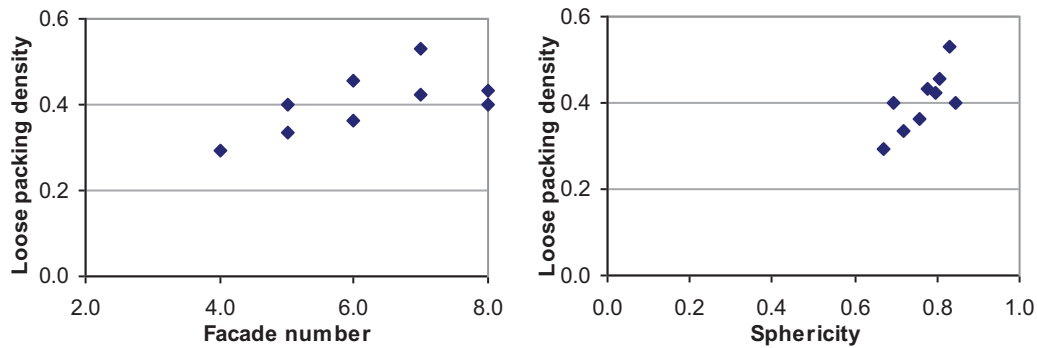


Fig. (7). Correlation between (left) facade number and (right) sphericity of grains at random loose packing density, respectively.

Recently, in a study of Erdogan *et al.* [36], the shapes of four different types of aggregate, GR, LS, IN, and AZ were investigated by computer tomography (CT) method and reconstructed by the spherical harmonic technique. The most interesting information from their shape analysis is the surface area (S) versus volume (V) information of each particle of different types of aggregate. A regression analysis based on the function $S = aV^b$ was accomplished for S and V data of each type of aggregate. The coefficients a and b for each type of aggregate are listed in Table 1 [37]. The variances of the regressions were all higher than 0.98.

Table 1. S - V correlation coefficients found by Erdogan *et al.* [36] for four types of aggregate; coefficient a^* and sphericity are based on regression analysis by the function $S = a^*V^{2/3}$.

Aggregate Type	Coefficient a	Coefficient b	Variance R^2	Coefficient a^*	Sphericity
GR	8.1	0.63	0.99	6.13	0.79
LS	7.5	0.64	0.997	6.12	0.79
IN	8.6	0.62	0.99	6.06	0.80
AZ	9.1	0.61	0.98	5.95	0.81

Since an ideal value of b in standard shapes is $2/3$, the regression function $S = a^*V^{2/3}$ was employed to fit different types of aggregate. For effective experimental conditions as to volume ($<4,000 \text{ mm}^3$) and size range, a^* is determined for each type of aggregate with a variation lower than 5%, as shown in Table 1. It demonstrates the crushed rock types GR and LS to have quite similar sphericity. The natural river gravel types IN and AZ have a larger sphericity as a result of their more rounded nature.

In a study [38], it is demonstrated in full detail how a mixture of different

polyhedra can be designed to simulate practical mixtures, such as those by Erdogan *et al* [36]. The results for the crushed rock aggregate mixtures as simulated by this so called *composite polyhedra method* are as an example displayed in Fig. (8). Similarity is very satisfactory. Specific surface area of the aggregate is an important performance characteristic that has influence on packing capacity and on shrinkage cracking, among other things. Surface roughness simulation can be achieved in HADES as well. Table 2 shows for different input parameters (related to the amplitude of superimposed goniometric functions) the resulting surface texture.

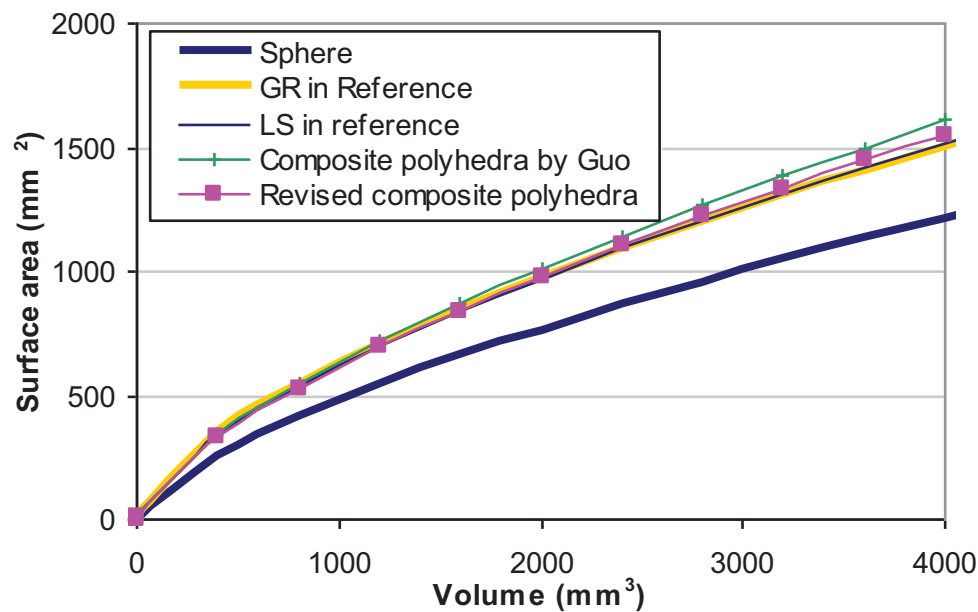


Fig. (8). *S-V* curves of crushed rock types (GR and LS), of composite polyhedra and of the sphere. Field data by Guo [38] were employed as well as revised data to get an even better correspondence with reference data from an experimental approach by Erdogan *et al.* [36].

Table 2. Surface texture simulation of an arbitrary octahedron for different amplitude values, A_0 .

A_0	0.01	0.03	0.05	0.10

3.2. Boundary Effects

Boundary zones are well-known in concrete technology. They develop in the aggregate structure near the formwork and near reinforcement bars. Precisely the same packing phenomenon is however evident in the binder structure near the surface of aggregate grains leading to the formation of the ITZ [3, 39, 40]. Boundary effects are the inevitable result of different physical dimensions of grains: the smaller ones can come closer to the rigid surface, so that a gradient structure develops. A multitude of publications can be found on the very topic. Less well-known in the concrete technology field is the Brazil Nut Effect (BNE). The name is derived from a mixture of nuts in a pot in which the largest ones will move to the top upon shaking the pot. Fig. (9) illustrates this by stills from a 2D simulation video.

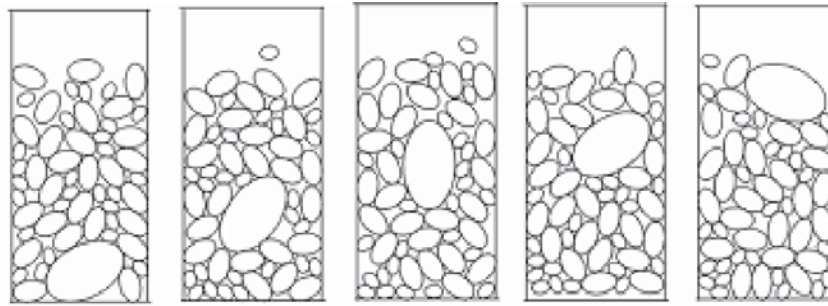


Fig. (9). Traditional Brazil nut concept: mixture of non-spherical particles of various sizes is activated by vibration at the bottom of the container. Stills from a video of a 2D simulation by HADES revealing the size segregation process [41, 42].

This has also been investigated by numerical approach: Fig. (10) at the left presents an example. BNE is a “newer” phenomenon; research is of more recent date. Fig. (10) at the right for aggregate.

Aggregate transported on conveyor belts also segregates due to BNE, as will be the case when transporting other particulate products in this way, of course. The phenomenon has received quite some attention in high-standard journals in the past decades [43 - 50]. The simplest situation is where the largest grains move upward during vibration. However, also the reversed phenomenon has been recorded. To complicate matters even more, also BNE perpendicular to the gravity field is observed. Extensive discussions on operating mechanisms can be found in the indicated articles to which the interested readers are referred. Obviously, various parameters of the concrete mixture decide upon what will happen in the realcrete. We have one experience with BNE in material research on meso-level. The program of material testing indicated in connection with Figure 4

- so concretes in which the largest grain fraction was replaced by 16 mm mono-size ceramic balls, revealed these balls to have segregated out of the center to the bottom and to the top. For that purpose, the 200 mm cubes that resulted after removing of a 25 mm surface layer from the originally 250 mm cubes, were sawn horizontally - *i.e.*, perpendicular to the gravitation field during compaction by vibration - into 11 mm thick tiles. Areal fraction was measured in the successive sections (two per tile). This can be associated with volume fraction of the steatite balls. It was plotted as function of the section location in the cube. The mixture with lowest fraction of ceramic balls revealed segregation in the gravity direction, however the one with highest fraction (and more extensively vibrated) showed significantly higher values at the top and bottom of the cube. The coarse aggregate had moved disproportionately to the top and to the bottom!

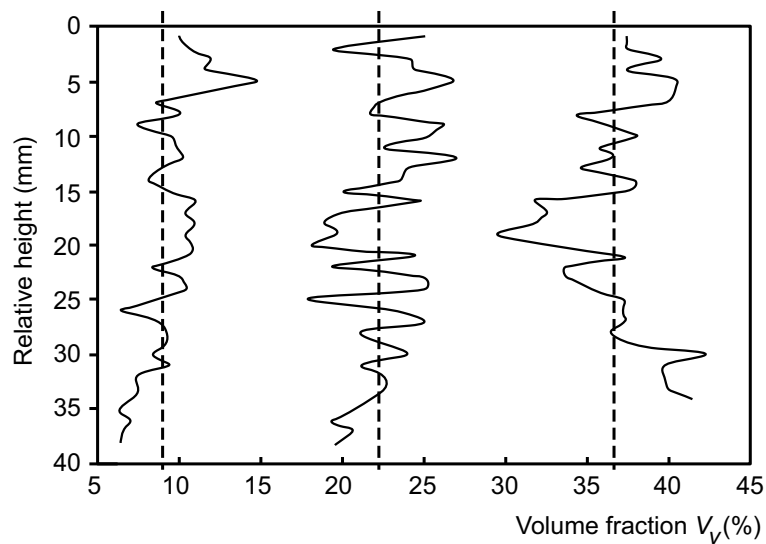


Fig. (10). Gradient structures in volume fraction (V_v) of coarse aggregate (dashed lines indicate averages in different concrete mixtures). Top of specimen is at the bottom of the scale [34].

Similar phenomena have been observed in virtual concrete when studying the binder structure. An example is shown in Fig. (11) [32, 40]. Although the major changes in the quite structure-sensitive parameter of λ^{-3} (λ stands for the mean free spacing of the cement particles) occur over, say, the first 15 μm measured from the aggregate grain surface at the left, the size segregation in the cement particle mixture penetrates much deeper into the paste, as revealed by the section patterns at the right. The ITZ effect on material properties can thus be due to a wider zone than the one in which the major changes occur in the measured parameter. This gradient in particulate structure pertains after hydration (simulation). This is shown in Fig. (12), also dealing with λ^{-3} as interesting material parameter (because

supposedly proportional to internal bond strength). Obviously, the normalized data of “bond strength” after 100 hours of hydration accurately match those in the fresh state.

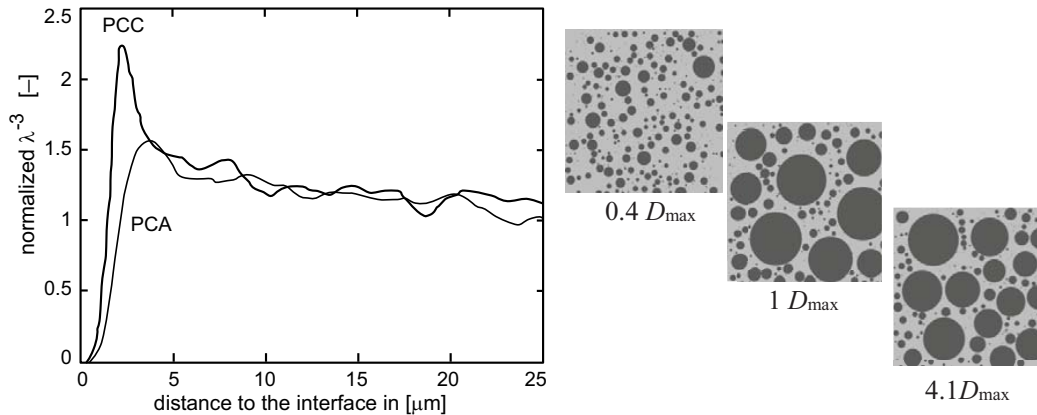


Fig. (11). (right) Section patterns through fresh model cement paste parallel to aggregate grain’s surface on distances of 8, 20 and 84 μm , respectively. The model cement paste was simulated by DEM [9]. Grading gradient extends due to BNE-driven size segregation far deeper into the cement paste than that of the wall effect ($\leq D_{\text{max}} = 20 \mu\text{m}$), witnessing a more extensive ITZ (left). Bonding capacity is assumed proportional to λ^{-3} , whereby λ stands for the mean free particle spacing; $w/c=0.2$; PCC is fine-grained cement; PCA is coarse-grained cement. Section patterns at the right at indicated distances to the aggregate surface.

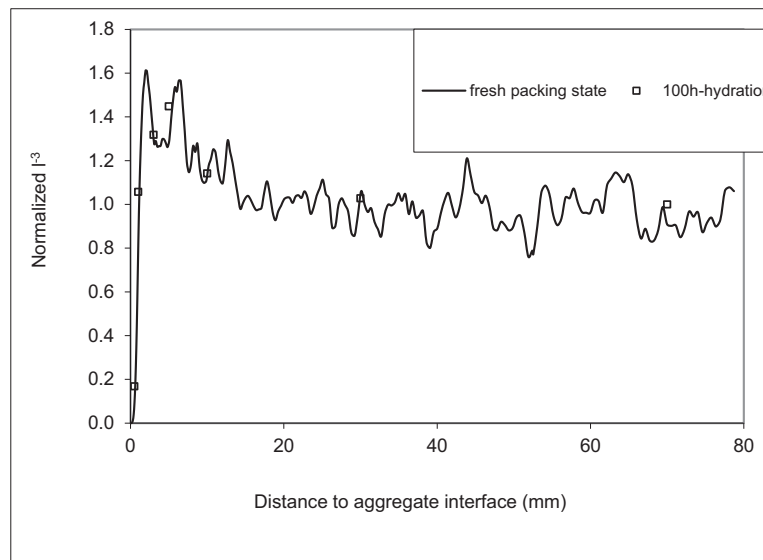


Fig. (12). Disproportional bond strength increase in the ITZ remains throughout hydration process [41].

4. PACKING OF FIBERS IN CONCRETE

As mentioned earlier, fibers are employed in concrete to control the process of micro-cracking, so provide the concrete with deformational capacity. Of course, properties that can be realized depend on the type of fibers and the applied volume fraction. Generally, the fiber factor $a\tau_f V_f$ with a as aspect ratio, τ_f as interfacial friction resistance and V_f as volume fraction is considered to be the major parameter governing the mechanics of fiber reinforced cementitious materials. Of course, their dispersion throughout the material is also of paramount importance, particularly in research where relatively small units are tested, as shown in Fig. (13). The prismatic specimens were subjected to direct tension in a stiffness-controlled testing machine in which they were glued. The final crack area is revealed. Different types of steel fibers were compared. For details of the testing program and obtained results, see [51]. The example specimen shown contains hooked-end steel fibers. The specimens were compacted by vibration to get the aggregate in a dense state. However, the steel fibers are equally compacted by vibration, yet segregated as well. Also this type of material features can be simulated by dynamic DEM. Basically, the larger aggregate grains in the compacted mixture provide for the space in which the fibers should find their location and orientation.

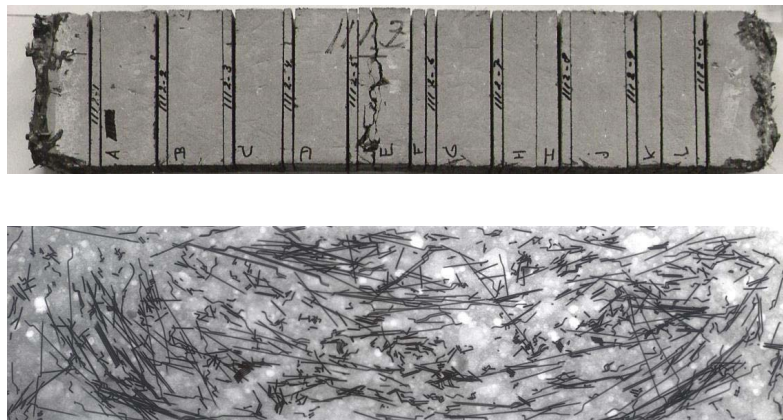


Fig. (13). Top: location of vertical slices prepared of prismatic steel fiber reinforced concrete specimen (1,000 mm x 200 mm x 50 mm) containing 1.72% by volume of hooked-end fibers. X-ray radiographs were prepared of all slices of which an example is presented at the bottom; this reveals steel fiber dispersion to be highly anisotropic.

5. DEM PACKING OF BINDER

The similarity of packing particles on the different scales in a numerical approach renders possible simulating realistically the fresh structure of the binder paste. Details of the methodology have been published [15, 52, 53]. This also involves

the hydration simulation by improved vector-based approach [54]. This provides the researcher with the hardened binder paste with developed pore network system. For porosimetry we have modified a robotics method for path finding [55] into an effective system of multiple trees growing into pore space, joining when in the same pore. It is called DRaMuTS, Double Random Multiple Tree Structuring [56]. For the growing of the trees, random points are generated that are connected by the tree branches without intersecting the pore surface. To do so, a point sometimes has to be shifted along the connecting line, violating the randomness. This requires the generation of a second random point system in pore space for measuring pore characteristics.

The resulting pore space is very complex, as illustrated by Fig. (14). Getting topological and geometrical information of such a structure requires a non-conventional approach. This is obtained from life science research and is denoted star volume measuring (SVM) [57]. It involves using all random points as nuclei of stars. The randomly or systematically generated pikes that run from the nucleus to the nearby pore surface are measured and their cubed values averaged. Finally, the third root value is an unbiased estimate for the radius of a representative sphere that characterizes local pore size [58]. Of course, the continuity in the tree channels defines the pore connectivity. The point density in pore space is a measure for local porosity. In cube specimens of the order of 100 μm base length, we generate 10^5 points in pore space (so, more points are generated in the cube) to arrive at a proper sensitivity level.

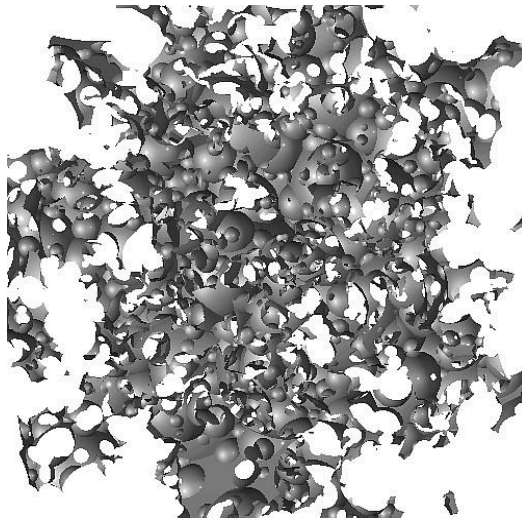


Fig. (14). Pore space in hardened cement paste after removing all hydration products as well as the unhydrated particles. Note the spherical nature of the elements building up this complex structure, which are due to the vector-based hydration simulation approach [9].

For estimating permeability, the pore network from tree channels is stretched by mathematical tools and a network analysis is conducted on the basis of pore element lengths between nodes and their size and shape [18, 58, 59]. The material is supposedly fully saturated. If not, it becomes an additional parameter dominating permeability (Fig. 15). This is demonstrated by experiments in the literature as well as by numerical simulation. Problems in matching experimental and numerical data are partly due to biasedness of the frequently employed MIP data [60], the difference between the concrete generally used in experimental investigation and the cement paste employed in the numerical approach (because of micro-cracking) and the uncertainty about the actual water saturation degree in the concrete. Fig. (15) shows the significant effect of a declining water saturation degree on pore size. This is realized in the numerical material by blocking pores after water evaporation; a process that starts from the largest pores. For low values of water saturation (say, below 0.4), moreover, pore connectivity drops down significantly, and so will do permeability [18].

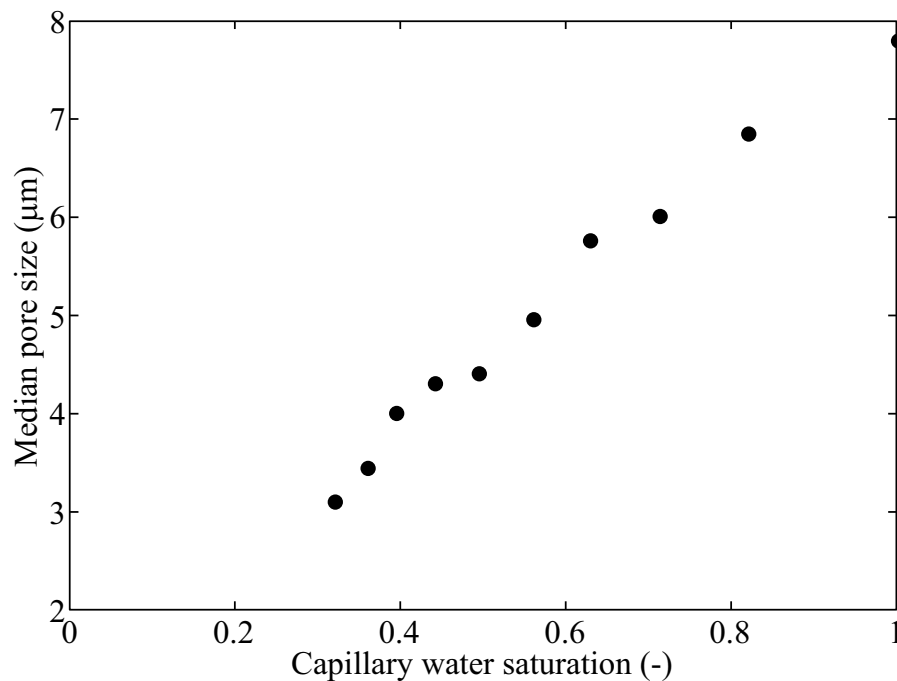


Fig. (15). shows an almost linear reduction in median pore size with a decline in water saturation degree.

Aggregate packing in numerical concrete can be conducted with actual sizes, of course, and with shapes resembling globally actual shapes in engineering practice. This can be realized by a single particle shape for river aggregate and crushed

rock, respectively. However, also composite structures may be formed in which surface to volume ratio is equal to mixes used in practice.

Recently, we demonstrated that aggregate packing resulting in ITZ percolation could thereby lead to increased permeability, as found in experiments [61]. It could however also lead to reduced permeability, as found in other experiments [62]. The key factor here - again - is the water saturation degree of the concrete. Anyhow, aggregate packing has many implications for properties of concrete. The studies of underlying mechanisms on properly simulated virtual cementitious materials render possible gradually shifting the frontiers of concrete technology. This holds for sophisticated special concretes, as well as for materials for low-cost housing developments [63, 64].

DISCUSSION AND CONCLUSIONS

Particle packing is a natural phenomenon. A large number of publications are available in various branches of science. Packing in nature, and also in concrete is frequently more complicated than assumed in such theoretical concepts. This is due to the fact that we deal with an unknown state between order and chaos. For the latter, ideal states, solutions can easily be generated. Limited space conditions exert additional influences, leading to the development of boundary zones that are referred to on micro-level in concrete as ITZs. Another complicating phenomenon depending on particle mix design and vibration characteristics is BNE. This may also occur on the different levels of the microstructure. In imitating natural behaviour, DEM provides an economic way to perform research into the various phenomena relevant for the design and usage of structural concrete in engineering practice. As to permeability estimation, the uncertainty in the water saturation degree in research (even for concrete kept submerged before testing) makes it difficult correctly interpreting the experimental data. Nevertheless, numerical investigations reveal this phenomenon in satisfactory agreement with latest experiments in this field.

Binder structures can be produced in the fresh state similar to aggregate packed on meso-level. Next, upon hydration simulation also the hardened state is obtained. The latter contains the pore structure we are interested in because of durability reasons. Sophisticated techniques render possible getting access to such complicated spatial structures and to obtain relevant information on topological and geometric characteristics relevant for permeability estimation.

Nature reveals aggregate to pack densely – and segregated, as demonstrated previously. The latter we try to avoid. The first we want to optimize, whereby it should be noted that optimum mix design is quite established. Yet, we still need a lot of research efforts. Such experiments are in the concrete field traditionally

time consuming, laborious and thus expensive. Fortunately, DEM can do the same but faster and more economic. Part of the insight is of course coming from mix design research. The packing optimization is a function of mix design. Top of the curve is close to the Fuller mix, indeed. This can be readily achieved in much shorter time by making numerical material, as is demonstrated. For preventing segregation, experiments have shown the amount of fines of paramount importance and the water to cement ratio, of course. This has also been investigated by numerical approach. BNE is a “newer” phenomenon; research is of more recent date.

The aggregate packing in compucrete has provided the way to operate similarly for packed binder particles. The (further) development of separate algorithms for hydration, pore delineation and pore measuring made the method also operational for durability research; a field where experimental approaches are by definition time consuming, laborious and thus expensive.

CONSENT FOR PUBLICATION

Not applicable.

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CONFLICT OF INTEREST

The authors confirm that this chapter contents have no conflict of interest.

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CHAPTER 6

Current Developments and Future Needs for Natural Earth Construction: A State-of-the-Art Review

Ana Cecilia Vieira Nóbrega¹ and Normando Perazzo Barbosa^{2*}

¹ Department of Civil Engineering, Federal University of Pernambuco, Recife-PE, Brazil

² Department of Civil Engineering, Federal University of Pernambuco, João Pessoa-PB, Brazil

Abstract: A more sustainable and conscientious world desires to go back in time to use environmentally friendly construction materials, earthen materials. However, the simplicity of such materials has not yet been properly addressed in either academic or field research; at the same time natural earth construction is far from mature. In this scenario, we summarize the development of natural earth construction during the last few years. Recent publications including a number of books and journals on natural building are reviewed, while emphasizing the impacts of field research. Controversies and gaps in understanding are identified, and we discuss the advances of these modern ideas through the years. Topics include a review of natural earth building; materials selection; property evaluation; academic and field studies; and a state-of-the-art review on current developments (Adobe, Compressed earth blocks, Cob, Rammed earth, Earthbag construction, Earth floors, and Earth wall finishes). Recent developments in standards for earthen building materials are also reviewed. This chapter concludes with perspectives and future needs in natural earth construction, those which may have significant impacts on the advancing field.

Keywords: Earth construction, sustainable building, stabilized earth, compressed earth block, rammed earth, natural building material.

1. INTRODUCTION

No material is more bio-inspiring and simpler than the earth. For thousands of years, humanity has had very little understanding concerning earthen material properties. As a consequence, the stigmas associated with earthen materials have generally included: failures in durability [1], low resistance strength [1], high shrinkage or cracking [1], and low mechanical strength [2] among others.

* Corresponding author Normando Perazzo Barbosa: Department of Civil Engineering, Federal University of Pernambuco, Recife-PE, Brazil; Tel: 5583981467225; E-mail: nperazzob@yahoo.com.br

However, this view has been changing with time. Currently, for example in the Southwest United States and other arid regions, Adobe and rammed earth constructions are resurfacing [3]. Globally, 40 percent of the world's population is housed in earthen shelters [3].

Today we understand that simplicity in earthen constructions need not be related to failures in academic or field research. Yet even though research has increased together with technical knowledge, the field is undoubtedly not completely established.

The objective here is not to define earthen techniques or demonstrate applications; or much less teach construction techniques or give tips for a successful installation; our goal is to provide a state-of-the-art review, a kind of timeline based on remaining controversies or gaps in understanding, on innovations and how to preserve the past conservatory ideas, on how the standards have matured or not, and on perspectives and future needs regarding earth building.

We hope that this review has a significant impact towards advancing the field.

2. AN OVERVIEW OF NATURAL EARTH BUILDING

Earthen buildings remember primordial humanity. Through time, with the advent of concrete and other building materials in certain places and conditions, earthen buildings have often been forgotten. Over time, their advantages, such as sustainability, green-thinking and a more conscientious relationship with the planet, have again redirected attention to earth construction, especially in developed countries.

However, earth construction is not viewed equally around the world. In most developing countries, an earth based building is used to minimize housing problems, as in for example stabilized earth construction, which is discussed in reference [4]. Earth construction remains associated with health problems, since empty living spaces often house Barber bugs, an insect responsible for transmission of Chagas' disease. When located in tropical climates with poor and precarious populations, this problem is accentuated.

In developed countries on the other hand, key-words such as technological advancement, industrialization, healthy indoor environments, energy efficiency, long-life, durability, low maintenance, improved acoustics, improved seismic stability and fire barriers are now associated with *modern* earth building [5]. A complete overview of modern earth building in developed countries can be seen in a study referenced as [5].

There have been discussions in the literature about using stabilized or unstabilized earth construction for contemporary urban housing [6]. In the case of construction to alleviate urban housing crises, Zami and Lee [6] suggest adopting an appropriate stabilized earth construction such as: rammed earth or compressed stabilized earth blocks, stabilized Adobe or other contemporary stabilized earth construction techniques.

3. SOIL - MATERIALS SELECTION FOR EARTH CONSTRUCTION

An excellent review on sourcing, extraction, and classification of natural soils (also called natural earth or naturally occurring clay, as well as defining construction soils is readily available [7].

Soil composition is essential to the properties of earth construction [8]. We know that to correct construction soils (addition of aggregates, dry soil, powdered clay, and/or additives [7]) before use, adjustments are frequently necessary. This guarantees the physical-chemical properties of both artisanal and industrialized products.

Usually, artisanal and industrialized product treatments are differentiated. While soil characterization for artisanal products can be very simple, using only manual testing; more precise and repetitive evaluations should be carried out for industrialized products.

Very elementary manual techniques can be used to evaluate soils, including hand contact and other simple tests. Such tests are well described [7]: and include visual assessment of grain composition, sedimentation (jar tests), ball tests, smell tests, and colors.

More details concerning such tests are well described in a study [7], including:

- i. Grain parameters (size, distribution, and shape of mineral particles), sieve analysis and hydrometer analysis;
- ii. Specific grain surface area;
- iii. Moisture content;
- iv. Plasticity index PI, consistency index CI, Liquid limit LL, Plastic limit PL and Shrinkage limit SL;
- v. Pfefferkorn Plasticity;
- vi. Standard consistency and cohesive strength;
- vii. Shrinkage;
- viii. Swelling;
- ix. Lime content;
- x. Water-soluble salts;

- xi. Organic matter;
- xii. Chemical-mineralogical and morphological parameters applying X-Ray Fluorescence (XRF), X-Ray Diffraction (XRD), and Scanning Electron Microscopy (SEM), among others.

Specific soil characteristics for earth construction are compiled in Table 1.

Table 1. Construction soil characteristics for earth construction applications.

	Grain Fraction			Plasticity and Consistency		Highlights
		Minimum [%]	Maximum [%]	PI	LL	
Rammed earth	clay + silt	20-25 [7, 9]	30-35 [7, 9]	0.03 - 0.30 [7, 10]	0.24 - 0.46 [7, 10]	- A well-graded (even and consistent) grain size distribution curve [7]. - Soils with mixed grain sizes including coarse grains (eluvial soils or glacial) [7]. - Lean to rich soil with low to medium cohesion [7]. - The addition of lime and cement binders is a common practice [7]. - A 7% cement stabilization ratio is roughly 13 parts soil to 1 part cement [11]. - In [179] the sandy laterite soil available in the tropical regions has been identified as a preferred ingredient for cement stabilized rammed earth construction which can offer adequate compressive and flexural strengths when cement content is in excess of 6%.
	sand + gravel	50-55 [7, 9]	70-75 [7, 9]			
Cob	sand	50-85 [12]				- Fine-grained soil, lean to rich, with low to medium cohesion (loess soil) [7]. - Be careful of crackings despite the reinforcement effect of the straw fibers [7]. - Rocky construction soils complicate the preparation process as well [7].
	clay straw	50-15 [12]				

(Table 1) cont.....

	Grain Fraction			Plasticity and Consistency		Highlights
		Minimum [%]	Maximum [%]	PI	LL	
Straw clay and clay with added fibers						- Lean to semi-rich soil, silty, with low cohesion [7]. - Suitable organic aggregates are soft straw, hay, or other soft plant fibers with lengths to 25 cm [7].
Light clay						- Lean with low cohesive strength (Loess soils) for heavy mixes [7]. - Rich to very rich or fine grained soils that have medium to high cohesive strength (fluvial soils, with some clay powder added) for light mixes [7]. - Aggregates can be organic fiber material (all types of straw, wood chips) and/or lightweight mineral aggregates (thermally expanded materials, pumice, perlite) [7]. - Mixtures of both types of aggregates are also possible [7]. - Organic fibers should not be longer than the shortest length of the finished building element or building material [7].
Earthen Loose Fill						- There are no specific requirements in terms of cohesive strength/plasticity and particle size of the construction soil [7].
Earth Mortars						- Earth mortars in general: Fine-grained, silty to sandy, and lean to semi-rich soils, and soils with low cohesion (e.g., loess soil) [7]. - Earth masonry mortar: lean to semi-rich soils and with low cohesion [7]. - Earth plaster or mortar: silty-sandy soils (loess soil) with a sufficient portion of coarse-grained silt, to medium-grained sand to reduce shrinkage. Soil should have a minimum amount of clay minerals. Correcting by adding clay powder [7].

(Table 1) cont.....

	Grain Fraction			Plasticity and Consistency		Highlights
		Minimum [%]	Maximum [%]	PI	LL	
Earth Mortars						- Sprayed earth mortar: semi-rich to rich soil and low to semi-cohesive [7]. - All grain sizes >5 mm must be screened out [7]. - Be careful with harmful salt concentrations [7].
Unstabilized earth blocks	clay + silt	78-91 [13]; 61-86 [13]		0.17-0.33 [7, 10]	0.32-0.50 [7, 10]	- Soil used for making earth blocks must meet the quality requirements of unshaped earth building materials, particularly with regard to cohesive strength and plasticity as well as grain size distribution [7]. - Lateritic soils have been successfully used in Africa [14].
	sand	8-18 [13]; 11-26 [13]				
	gravel	1-4 [13]; 3-13 [13]				
	Adobe straw fiber content (%)	20-40 [13] 15-28 [13]		0.14-0.21 [13]; 0.09-0.13 [13]	0.42 -0.46 [13]; 0.35-0.37 [13]	
Stabilized earth blocks				0.273 [15]	0.145 [15]	- Soil must meet the quality requirements of unshaped earth building materials [7]. - Stabilized earth blocks contain chemically modifying additives which alter the blocks' water solubility and strength [7]. - Lateritic soils have been successfully used in Africa [14].
Clay panels						- Soil must meet quality requirements for unshaped earth building materials [7]. - Cohesive clay powders or dry soils amended with sand are used for "thin" clay panels while rammed earth is used to produce solid panels (wall panels) [7]. - Lime and microsilica (or silica fume) have been used to stabilize problematic silty sands [16], saline silty sand [17], and soft kaolin clay [18].

(Table 1) cont.....

	Grain Fraction			Plasticity and Consistency		Highlights
		Minimum [%]	Maximum [%]	PI	LL	
Earthen floor						- Straw/clay Adobe base: 25-35% clay soil, 65-75% sandy/gravelly soil, and a good amount of chopped straw [19]. - Final layer: 25% clay and 75% sandy soil, screened through 1-4 inch screen, or use 1/8 " screen fineness [19].

4. DURABILITY OF EARTHEN CONSTRUCTION

The greatest concern of the general public interested in earth construction is durability [20], and unfortunately, there is not yet enough conclusive data or specific research. However, earthen construction does have considerable durability when properly prepared [21]. Evidencing this, earthen masonry structures having survived for than a 1000 years can still be found [21].

Water erosion, as suffered by the external surfaces of earthen buildings, is a critical problem, especially in countries with high levels of rainfall [20, 22 - 25]. Rainfall intensity and angle, the extent of overhanging eaves, and wall roughness are important factors which can influence the process of erosion [20]. Erosion durability test proposals are also presented and described [20]. In general, to explore durability for development of an earth product or an earth construction process, a climate simulation chamber should be used [26].

The durability of an earth based construction project is generally closely related to its moisture buffering capacity [27 - 32]. Water penetration is an important factor affecting rammed earth construction durability [33]. In the case of unfired blocks, it appears that to buffer against humidity, soil selection (mineralogy and particle size distribution) is more important than density, preparation methods, or soil stabilization [27].

Of a set of stabilized and unstabilized rammed earth walls studied through exposure to a wet continental climate, after 20 years of exposure to natural weathering [23], none of them presented complete collapse. The results revealed that the mean erosion depth of the studied walls (rammed earth wall stabilized with 5% by dry weight of hydraulic lime) was about 2 mm (0.5% wall thickness), and in the case of unstabilized rammed earth walls, it was about 6.4 mm (1.6% wall thickness). Stabilization permits avoiding plaster wall protection. The authors

highlighted that in the case of unstabilized rammed earth walls, an extrapolated lifetime of longer than 60 years can be expected. Further information on durability and sensitivity to water for rammed earth structures can be seen [34].

Currently, for improving earth construction durability, we find that not only erosion, but also water penetration, water permeability and water vapor permeability are in focus [22]. For example, a small amount of cement is already being consecrated for improving the durability of rammed earth structures [11, 33]. Nonetheless, due to the hydrophilic nature of the earth/cement material (attracting water penetration), problems associated with water penetration still cannot be totally avoided [33]. For rammed earth durability, walls made with heavy clay soils present improved durability characteristics if course thickness is set to 5 inches or less. Sandy soils in some cases yield satisfactory compaction at much larger lift thickness (12 inches or greater). These suggestions can be found in the study referenced as [11]. Specialized curing techniques, (of at least 28 days), are also essential to improve rammed earth durability [11].

Thus, in this field, new methods involving: a) incorporation of biopolymers [22, 35]; b) addition of minerals (sodium hydroxide, sodium chloride, sodium silicate, calcium chloride and sodium borate [22]); c) stabilization with lime [22] and pozzolans [15, 22, 36 - 41], have improved ancient techniques.

A Table found in [22], compiled and separated by country and application, discusses biopolymer(s): techniques, materials, and properties; and ancient earthen construction: techniques involving flours, starches, gums, oils, waxes, sugar, casein, glycerol, water with cellulose, plant resins, and animal fats, whey, casein, egg whites, blood, excrement, and urine (all of animal origin) [22, 35]. The durability of such oil-based or fat-based admixtures compared to that of the new silicone water-repellent admixtures is also well discussed [33].

Adobe is probably one of the best examples of the durability and longevity of earthen construction [42], but this obviously depends on the quality of the brick [43]. For locally produced Adobe, small amounts of hydrated lime or natural fibers are added to the soil matrix [44]. See reference [45] for complete information on Adobe conservation. Fibers have been cited as elements that improve the durability of stabilized soils [46]. The type of the fiber, its tensile strength and durability; the fiber length and volume fraction in the composite mix are all very important to the final result [44]. In Adobe structures, plastic binders in the earth-mix and improved stucco systems have also been used to increase water resistance, thus allowing earth construction to spread beyond arid regions to more humid climates [3].

The durability of a Cob house is directly related to how much energy the builder

puts into the job, including the mix composition [43]. With Cob houses, the builder is responsible for the results [43]. For [47], a sufficiently strong rammed earth can be used in very cold and wet climates and should be carefully considered [48, 49]. Compression strength is the single biggest determinant of durability in rammed earth [47], and using a hydrophobic admixture can also be helpful. Examples of rammed earth work: done well in extremely cold, very wet, and very dry climates demonstrate the versatility of rammed earth [47]. Stabilization is used in North American-style rammed earth structures when there is a structural or durability requirement [47]. China is also exerting efforts to evaluate the durability of modern rammed earth construction [50].

Stabilizers improve the durability of earth systems [2, 20, 33, 43, 46] and avoid applications of expensive surface treatments for durability and water tightness [46]. In general, inorganic binders can be used [46]. Of stabilizers tested using [20] cement, lime, cement plus lime, and cement plus latex resin; cement plus latex resin presented the highest durability. Under real climatic conditions in Biskra (Algeria) [51], and after four years of exposure, treated walls showed no signs of deterioration. Yet more severe laboratory testing conditions, (as compared to the natural climatic conditions of Biskra), also presented excellent systemic behavior [51]. Four accelerated tests used to assess durability in stabilized blocks are well presented [24].

Cement stabilized materials (such as rammed earth) rarely present expressive durability problems [46]. Integral admixtures play an important role in rammed earth [33] and include: a) silicone water-repellent admixtures; b) stearates or oleates as water-repellent admixtures (which lack long term durability); c) plasticizers; d) and accelerators or retarders. All of which may be applied to rammed earth materials. These last two admixtures are less useful, but under special circumstances, can help to achieve certain desired properties [33].

The use of bitumen as a stabilizer is also cited [43, 46], as a waterproofing element rather than a binder. The use of quicklime for soil stabilization through hot hydration processing is beneficial to earth constructions; improving durability, mostly through moisture resistance [22]. Simultaneous additions of used oil or sodium hydroxide can enhance mechanical performance even more, due to quicklime [22]. Addition of sugar cane bagasse ash 10% in combination with 10% lime can significantly improve durability in compacted soil blocks [52].

Water repellent properties can be also achieved using hydrophobic organic polysiloxane [33, 53], either as a thin film impregnating the capillary wall surface of mud bricks to masonry substrates [53] or to chemically bond rammed earth [33]. The first case, brick surface impregnation with soluble sodium silicate

followed by water-based organic silicone emulsion is discussed in a study referenced as [53]. The mud brick surface can be consolidated by silicate pre-impregnation as well [53]. In the second case, rammed earth durability is also significantly improved by incorporating silicone water-repellent admixture or silicone water-repellent sealers as integral admixtures [33]. In practice, the durability generally lasts over 10 years with silicone sealer treatments [33].

In addition, nanotechnology silicone water-repellent admixtures applied to the structure have been used to achieve vast improvements in rammed earth durability [33].

The earthbag is highlighted over other earthen ancient building methods [42] as offering superior durability in domed and vaulted assemblies, especially when a protective rock veneer was added to the exterior face as a splashguard [42]. We should remember that sand-bags are used to control floods and erosion in many situations [43]. Coating can improve internal and external durability [43]. For exterior applications, stabilizers can be used in such coatings and as salts are more durable in limewashes [43], casein [43] or silicone based water-repellent sealers [33]. Using diluted casein paint as a primer may also be a good idea [43]. A silicone water-repellent sealer can be applied like a finish sealer to further improve durability of both the render and of the rammed earth wall behind the render [33]. As such, a 90% reduction in water absorption while maintaining vapor permeability above 80% for the earth substrate has been reported.

Currently, for exterior tabique walls, metal corrugated plates, schist tiles and ceramic tiles are often applied as coating solutions. The main function of such building solutions is to increase the durability of the tabique wall by improving its waterproofing [54]. An important practical point concerning durability; is that extreme differences between mortar and brick durability should be avoided since this may accelerate weathering [21]. For example, an Adobe wall with Portland cement mortar between the bricks presents problems [21].

5. ACADEMIC AND FIELD RESEARCH IN NATURAL EARTH CONSTRUCTIONS: A STATE-OF-THE-ART REVIEW WITH CURRENT DEVELOPMENTS

This topic discusses research that has enhanced our understanding of how different earth materials and systems perform. Resources for further research including definitions, as well as technique developments are compiled in Table 2. Information on important developments can be seen in Table 3.

Table 2. Resources for further research.

Theme	Books, etc.	Complementary Books and Papers
Blocks: Adobe and compressed earth blocks	[55 - 68]	[1, 45, 57, 63, 66, 69 - 100]
Cob	[101 - 108]	[7, 69 - 71, 109 - 117]
Rammed earth	[65, 90, 118 - 128]	[69, 70, 91, 110, 129 - 131]
Earthbag, Super Adobe	[42, 43, 132]	[57, 65, 69, 77, 90, 133 - 141]
Earthen floors	[62, 77, 134, 142, 143]	[71, 101, 105, 144 - 150]
Earth exterior and interior wall finishes	[7,56,62,69,71,91, 105,117,129,151 - 158]	[42,43,107,109,118, 146 - 148,159 - 166]

Table 3. Information on important developments concerning each theme studied.

Blocks: Adobe
• a. The bee <i>Centris muralis</i> Burmeister (Insecta: Hymenoptera: Apidae) was recognized as a biodeterioration agent for Adobes [99]. • b. For compressive strength testing, equations, and modeling of Adobe bricks [13, 98, 167] for walls [168], including seismic reactions. There is still a need of standardized tests and empirical manipulation [13]. • c. Data concerning thermal behavior of Adobe bricks and walls can be seen in [169 - 173]. For variations in weather, climatic region, external wall thermal conductivity, window size, as well as the presence or absence of internal walls and influence on Adobe wall thermal behavior [171]. • d. For embodied energy, energy payback time for the Adobe house was 1.54 years, and approximately 370 GJ energy can be saved per year, compared to a conventional building [174]. • e. The use of fibers in mud bricks are reported in [175].
Blocks: Compressed Earth
• a. Typical strengths of the bricks made at laboratory scale was lower than the industrial scale [37]. • b. Stabilized compressed earth bricks can be made using just cement and-or lime [1, 15, 37, 38, 40, 176 - 178]. • c. Information on Pozzolanic stabilization methods [38, 40, 41] using sugarcane bagasse ash [15, 36, 52], ground granulated blast furnace slag [37], metakaolin [38], coastal solonchak [39], and volcanic ash [40]. Positive changes in compressive strength can be achieved through the addition of metakaolin to cement and lime stabilized extruded earth masonry units [38]. 5% lime and 10% metakaolin would allow unfired extruded earth masonry units to be used for structural applications [38]. The addition of 10% sugar cane bagasse ash in combination with 10% lime significantly improves the mechanical properties of compacted soil blocks [52]. The bearing strength of sandy loam soil compressed earth block bricks was improved using sugarcane bagasse ash [36]. • d. Alkaline activation as another possibility to stabilize soil [179, 180]. Although future research improvements are necessary, Silva <i>et al.</i> [180] found that granitic residual soil requires chemical stabilization using alkali activated fly ash and substantially improves the strength of compressed earth blocks. Thermal performance of masonries made of Interlocking Compressed Earth Block (ICEBs) when stabilized with alkali-activated fly ash [179] presents an improvement when stabilization is done with alkali activated fly ash as compared to other earth based materials. ICEBs can be recommended for regions with temperate climates [40].

(Table 3) *cont....*

• e. The combination of stabilizing methods has also been reported [1]. Good compressive strength and better durability at a reasonable cost were achieved by [1] using a combination of a mechanical compaction and chemical stabilization with cement (or sand and cement) within limits. • f. Stabilized compressed earth blocks with coastal solonchak in activation pretreatment [39] improves both strength and water resistance. • g. Thermal studies are published in [181 - 184]. Sassine <i>et al.</i> [184] present a very interesting frequency domain regression method to predict brick wall thermal behavior in existing buildings. The influence of external shading on optimum insulation thickness of building walls in a tropical region, including earth walls, was also investigated [184]. In a study [183], the addition of fiber positively improved both thermal and static properties. Bricks reinforced with barley straw fiber exhibited high thermal insulation values [183]. Of all investigated variants, thermal conductivity decreased with increasing fiber content and also with higher cement and gypsum contents [183]. Depending on the soil used, the optimum wall thickness for unfired earth bricks was 0.3 m - 0.4 m, ensuring greater heat capacity and thermal lag of between 10 and 12 hours [182]. A layer of an insulation material should be added to the wall to comply with thermal requirements [40]. • h. Soil blocks (stabilized using steam-cure) for masonry construction is another research avenue [185]. Energy-efficient steam cured soil blocks (consuming 35% less thermal energy if compared to burnt clay bricks) present high compressive strength ($>10 \text{ N/mm}^2$) and could be easily produced in a decentralized manner using expansive soil, sand, and fly ash combinations. Combination stabilizers (lime + cement) yield higher strengths than lime alone [185].
Cob
• a. Cob is one of the least studied load bearing earth construction techniques [107]. • b. Recently, a complete review of Cob construction entitled: "Cob, a vernacular earth construction process in the context of modern sustainable building" was published [107]. The authors begin with a clear definition of cob, a summarized description of the processes and strategies used to manage shrinkage cracks, and criteria concerning the qualities of implementation. An important list of traditional fibers and their characteristics when employed in Cob is also presented.
Rammed Earth
• a. Rammed earth sample production: context, recommendations and consistency are to be found in a study [34]. • b. A complete overview of modern rammed earth construction techniques with emphasis on current practices in the United States can be seen in another study [11]. • c. Modern earth construction in China can be explored in Wallis [50]. • d. Modern approaches in reinforcement and stabilization methods [11]. • e. Case studies have been published with useful field information, in Western Australia [186, 187] and in China [188]. • f. Modern approaches aim to better control the soil used in rammed earth [29, 30, 50]. Indications for soil suitability in rammed earth are well described and include contradictory indications concerning soils [189]. • g. Rammed earth can be used stabilized or not [50, 190, 191]. Although modern rammed earth structures seek to reduce or eliminate the use of cement [50], research on cement stabilized rammed earth has been recently published [192 - 194]. Dry hydrated lime $[\text{Ca}(\text{OH})_2]$ is also currently used as a cement binder for rammed earth [193 - 195]. The possibility of cost-effectively building insulated multistory structures is explored in a study [50].

(Table 3) cont.....

• h. The particle-size distribution of a soil has an important role in determining: the rate at which moisture invades rammed earth [30], interference in thermal conductivity [29], the rate of capillary suction [30], the absorption distribution of static pressure-driven water [31], and the sorptivity, surface receptiveness, and surface inflow velocity [32]. More precise information concerning each effect can be seen in references [29 - 32]. • i. Mechanical characteristics of rammed earth are shown in some studies [30, 196 - 199]. Studies quantifying strength gains through varying key parameters (binder content, dry unit weight) are still limited [195]. Suction plays an important role in strength in unstabilized rammed earth materials through variance of relative humidity [190]. • j. A study proposes that rammed earth material, if the layers remain adherent to each other, is an isotropic material of the first order [197]. In a study [195], we find equations that quantify the effects of parameters (dry unit weight, lime content, and fly ash content) on the compressive strength of Botucatu residual soils, and fly ash and lime blends; seeking to minimize resource consumption and maximize reuse/recycling for a desirable compressive resistance. • k. Fracture energy of stabilized rammed earth was evaluated in a study [200], when supplemented with cement or wool. • l. Textile-reinforced rammed earth is proposed as an innovation [201]. • m. Historical rammed earth process descriptions [202], and wall material compositions [203] were used [202, 204], and a promising micromorphological analysis gives information on mixing degree and water content at implementation [202]. • n. Phase change materials (commercialized straw, lime, and alabaster powder) can be successfully used to optimize and improve the thermal properties and life cycle of stabilized rammed earth [205]. • o. Thermal behavior of rammed earth can be seen in some studies [187, 206 - 208], as well as living-comfort evaluations [209]. Temperature profile evolution in stabilized rammed earth walls can be seen through transient numerical and physical modeling [210]. Reduction of wall thickness using rammed earth strongly penalizes its thermal behavior [206 - 208]. Insulation panels can be added to the outer faces of rammed earth buildings to improve their thermal behavior [206]. The effectiveness of thermal charging and discharging of earth-rammed thermal mass can be seen in some studies [211]. • p. Proposals for self-compacting rammed earth construction [212] and soil stabilization using alkaline activation with fly ash [212] represent an innovation. • q. Alkaline activation is explored as an alternative method for consolidation of historical earthen architecture [213], and also to improve properties of new constructions [180, 212].
Earthbag and Super Adobe Construction
• a. These systems are helpful to reconstruct disaster devastated communities, as well as for new constructions with a local material. A 'Super Adobe' dome shelter, of up to 16 feet wide, can be built in a single day by a family of four [138]. • b. Ventilation of a prototype of Super Adobe system was analyzed, as well as the lighting and insulation in study [214]. • c. Simple, rational, and comprehensive, design methods for earthbags and Super Adobe walls and domes were presented including geometrical and mechanical variables [215]. Information about differing geometries and computer-based optimization (how to) can be found in some studies [216, 217].
Earthen Floors
• a. Earth floors are cheap, beautiful and quite durable [142, 149]. • b. They are not to be used only in earth constructions, they can go as a slab on grade, as a slab on new or old concrete, or as a slab on new or old framing [218].

(Table 3) *cont....*

• c. The consensus is that a typical earthen floor includes a build-up of layers, each one with a specific purpose. Usually, we find a substrate, covered by a capillary break, a vapor barrier (polyethylene sheeting [149], polypropylene bags [150]), and an insulation layer. In sequence, we have the base layer covered by the leveled layer. Red pumice or scoria can be used for insulation, breaking capillarity at the same time [150]. Finally, we finish using a thin top layer of clay or clay paint [149, 150]. • d. Some builders speak of using a final hardening or 'drying' oil layer to impermeabilize the floor [150], as well as to achieve a super quality shiny finish [150]. Linseed, Walnut, Tung, Hemp, and Perilla oils are all hardening or 'drying' oils [150], forming an elastic film, and cure in contact with the air [150]. After curing, a coat of wax for the final touch is indicated [150]. Re-waxing should be performed every 1-5 years depending on the use [218].
Earthen Exterior and Interior Wall Finishes: Render, Finish Plasters, Paints and Earthen Pigments
• Using earth plasters for protection of earthen building is essential to protect this. The effects of different admixtures and surface treatments were studied in a study [25]. • b. Natural paints using readily available ingredients such as clay, gelatin, linseed oil, and artist pigments can be seen [219]. • c. Mortars to be applied as renders (for historical buildings) should take into consideration results from laboratorial tests, to evaluate their behavior in Adobe walls, and/or applied to Adobe walls [220]. • d. Mortars based on air lime–metakaolin–sepiolite lime were proposed as renders on Adobe walls [220]. • e. Instead of hydraulic lime or cement based plasters, total embodied energy can be reduced by using earthen plasters [221 - 223]. • f. Earthen pigment guidelines can also be found [224, 225] which are helpful in field-application practices which can be found on websites of Dancing Rabbit Ecovillage [226] and Quinta do Vale [227]. Building performance and sustainability of earthen plasters based on illitic soils from the Barrocal Region of Algarve (Portugal) are described in reference [222]. • g. The addition of natural fibers is a good alternative for improving flexural and compressive strength [222, 223], linear drying shrinkage [223, 228], and thermal conductivity [223] in earthen plasters. Benefits involving improved adhesion strength by mixing plaster into the substrate have been described in a study [223]. The type of fiber has an influence on improvements in mechanical resistance, as does the hygroscopic capacity of the plaster [223]. Results from oat straw and Typha fiber-wool are discussed in [223]. A review about plant aggregates and fibers in earth construction materials can be found in reference [229]. Three fibers (wheat straw, barley straw, and wood shavings) were also evaluated in earth plaster for straw bale buildings in terms of equilibrium moisture content [28] and shrinkage behavior [228]. • h. The results of a study [28] showed that the equilibrium moisture content of plaster materials increases with increasing relative humidity and decreases with rising temperature. Barley straw provided higher equilibrium moisture content than other materials examined. In addition, the Guggenheim-Anderson-de Boer (GAB) model was successfully used for predicting the equilibrium moisture content of earth plaster in straw bale constructions. • i. Shrinkage crack formation decreases with increasing fiber content and increases with increasing soil content [228]. The authors also highlight that in general, a lower curing temperature and higher fiber content are to be preferred to improve the performance of earth plasters. • j. A published document [230] presents a holistic approach, combining mineralogical, geochemical, and textural data to characterize decorative earthen plaster 2nd century Buddhist rock cut caves; the Karle caves of Western Deccan, India. • k. For Stazi <i>et al.</i> [25], earth plaster treated with the silane–siloxane product was found to be the best: fully compatible, water-repellent and highly resistant to water erosion; hence, the potential for using earth plasters to protect earthen buildings against weathering.

6. DEVELOPING EARTH CONSTRUCTION BUILDING CODES, STANDARDS, AND NORMS

Excellent accounts of the origins and evolution of Earth Construction building codes, standards and norms can be found in two recent books by Schroeder [231, 232]. In a study [231], published in 2016, a history of Germany's Earth Building Regulations to the present is included, as well as an excellent review concerning world-wide earth building regulations. The newly published DIN standard for earth building materials is also discussed.

Schroeder [231] has compiled 39 different regulations in 19 countries and regions. In some countries, earth building regulations have even become a part of general building regulations. Local organizations and building associations routinely publish directives on earth construction. A complete table of the countries, and their respective standards and normative publications for earth building can also be found [231, Table 4.3, pages 283-285].

Now decades after the first standards have been published, and as compared with other conventional building materials and construction techniques, there are still very few earth building standards, codes, or norms. Schroeder [231] agrees, and further adds that standardization is one of the crucial areas needed for general acceptance of earth as a building material. The fact that earthen building is an owner-builder material associated with do-it-yourself criteria makes the development of regulations difficult in the long term. Yet, as part of a long term change of vision, all earthen materials are now found industrialized in Germany [231],

It is believed that owners and builders are already convinced of the need for standardization; both for safety and construction quality, and this must include an international standardization. However, earthen construction does not involve conventional building materials, much less conventional techniques. This makes interest in standardization problematic.

For Schroeder [232], the internationally accepted standardization terminology is still lacking for earth construction. For development in the future, Schroeder [231] sees the necessity of viewing earth building as an "engineered construction technique", as is masonry or concrete. Other points highlighted by Schroeder [232] are the needs for a completely new generation of building standards, including durability, material life cycle, and problems. All of these arguments are in favor of using earth building materials as an ecologically sustainable and secure building option for today and for the future.

7. WORLD INNOVATIONS IN EARTHEN CONSTRUCTION

The Institute for Advanced Architecture of Catalonia (IAAC), based in Barcelona, recently proposed a new systemic method of research called PYLOS (Large Scale Additive Manufacturing - Printing with Natural Materials). It uses a large scale 3D printing system working at a large scale for earthen construction methods. The soil is mixed with other ingredients, including natural additives.

Embodied energy expenditures (fabrication processes, transportation hazards, independent energy/electrical production, fuel use, and greater environmental greenhouse effects) are greatly decreased (by more than 96%) when using the soil based construction system. In addition, IAAC research guarantees that all soils in the system can be recycled for an extremely long time period (indefinitely), and of course, old dry loam can simply be reused after soaking in water.

More information, texts, pictures and videos can be seen on the webpages: <http://pylos.iaac.net> and <https://iaac.net/research-projects/large-scale-3d-printing/pylos/>.

8. FUTURE NEEDS IN EARTH BUILDING

Improvements and adaptations in earth construction (as related to globalization and internationalization) must be taken into consideration. To develop competitiveness; considerations must include among others: a) reducing the cost of construction [11], b) overall living comfort [218], c) avoidance of toxic chemicals or products [218], d) use of natural impermeabilizing products to improve water susceptibility, e) use of novel additives and innovations.

Thus thinking in increasingly sustainable ways, a balance involving energetic opportunities [187, 206, 218] should be taken into consideration, including using residues, and earth provided sub-industrial demolition products as raw-materials. Use of quarry waste and recycled materials is discussed in a study [11, 50] for rammed earth, with an emphasis on higher scores in the LEED rating system. And finally, developing subsidy programs and incentives which support low-carbon thermal storage wall systems is mentioned in a study referenced as [11].

In developing countries, earthen construction is still socially stigmatized as the use of "opoverty" materials by "opoor" people to build ugly, weak, or badly renovated houses. To change this view, awareness campaigns are necessary to highlight how beautiful, secure, durable, and inspiring earth based constructions can be. Both the population and builders should be inspired. Zami and Lee [233] confirm our position when they defend that: "Earth construction is not just for the poor, but for the rich as well".

Another action-point would be to introduce earthen construction as a current mandatory discipline in Civil Engineering and Architecture Universities, as well as in technical Civil Construction courses. Thus, technical knowledge of earth based construction in the world would spread greatly with time. For Zami and Lee [233], ignorance is a major inhibitor influencing adoption of this technology. Development in terms of university and field research is also necessary, from replacing cement in stabilized walls to developing additives for weather-proofing [50].

In this same spirit of education, Easton and Easton [11] highlight points to help rammed earth gain usage in the construction industry. One idea is to expand the pool of trained installers [11] and teams working on specialty projects [50]. We completely agree and see a generalization of their vision for all earth constructions. Yet not only for installations and projects, Wallis [50] also highlights the importance of trained maintenance teams. Such traditional craftsmen are becoming scarce [233].

To publicize and internationalize standards it will be easier as more technical/research development becomes associated with earthen construction. Our opinion is the same as that established by some authors [11]; to improve the acceptance of rammed earth: promote and compile test data to define formulations, and to document structural performance [11].

Another important point to improve applicability of earth construction is mentioned in a study [50] for rammed earth, yet this could be extended for all systems: "Developing high-performance hybrid systems designed to solve the challenges presented by modern high-performance buildings".

In developing countries, the point is more delicate. First, it is necessary to change the general societal vision of earth construction. For this, we propose commencing new constructions, new studies, and the development of new standards. In each instance, creating more successful experiences with more precise, mature, and scientifically supported data is the key to growth.

FINAL CONSIDERATIONS

The potential of earthen construction is being rediscovered; though mainly in developing countries. In developed countries that have already recognized the importance of earth building, energy is being directed to standardize and internationalize standards and terms. In both cases, and in order to consolidate the quality of earth building and its potential applications, it will become necessary to improve technical and research databases.

A complete list is available [233] concerning influences that are currently inhibiting adoption of contemporary earth construction, with discussions in general (validated through the Delphi technique). A good reading will help to avoid negative points and improve positive ones, while increasing chances to incorporate earthen construction as an engineered system.

A better understanding of durability and its prediction along time in different situations is also a necessary condition for earthen systems to gain acceptance as a modern building materials. Durability, fire resistance, water vapor diffusion, and fungal resistance are also important points that need to be evaluated further [234]. Biodeterioration, in general, must also be taken into consideration [99].

Earth construction is growing and maturing in the field of construction, and will help people to solve habitation problems in poor areas of developing countries, as well as help reduce energy consumption worldwide.

Finally, it is important to highlight that by working together: earth builders, universities, researchers, grant agencies, and governments as well as international and national organizations, may spread earth construction's potential and possibilities around the world. All such efforts are important for integration (or re-integration) of earth construction into our common construction practice.

CONSENT FOR PUBLICATION

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CONFLICT OF INTEREST

The authors confirm that this chapter contents have no conflict of interest.

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Bio-inspired Design with Bamboo

Normando Perazzo Barbosa^{1,*}, José Augusto Gomes Neto¹, Sandra Reyes Ortiz¹ and Khosrow Ghavami²

¹ Federal University of Paraíba, João Pessoa-PB, Brazil

² Pontifical Catholic University of Rio de Janeiro, Rio de Janeiro, Brazil

Abstract: This chapter intends to present general information about bamboo; the fast growing grass with excellent mechanical properties. The potential of this material for Architecture and Construction is discussed. Information concerning how to obtain the plant and select appropriate culms/stems, to be employed for building is explored. Physical properties as revealed through research in Brazil are also presented. As for bamboo's mechanical properties; compressive, tensile, and shear strength parallel to the fibers are presented along with numerical values for various species. Specific applications for bamboo, such as concrete reinforcement are also presented. And finally, the potential of bamboo vessel impregnation with polymeric resins is described.

Keywords: Bamboo, Mechanical Properties, Polymeric Resin, Impregnation.

1. INTRODUCTION

Industrialized materials can mobilize vast financial resources; they consume an enormous amount of energy, and require a centralized process that results in higher costs for much of the world's population. Such materials regularly produce environmental pollution and residues in large amounts which are difficult to reincorporate with nature. In this sense, it is clear that ecologically friendly materials may well meet certain fundamental and current demands of society, such as: minimizing energy consumption, conserving natural resources, reducing pollution, and maintaining a healthy environment. Ongoing research on non-polluting materials such as vegetal fibers, bamboo, and earth is intense. These materials have been presented as construction alternatives, and based on their performance, they could be of much more use where they are found in abundance;

* Corresponding author Normando Perazzo Barbosa: Federal University of Paraíba, João Pessoa-PB, Brazil; Tel: 5583981467225; E-mail: nperazzob@yahoo.com.br

such as in developing countries. Of these materials, bamboo presents excellent potential.

Of the several favorable characteristics that bamboo presents for use in architecture and engineering, we highlight [1]:

- i. Lower energy consumption, compared to other materials such as steel, concrete and even wood, which can result in lower construction costs;
- ii. Short growth cycle, high and constant productivity;
- iii. Low specific weight, reducing the cost of handling and transport;
- iv. Finished tubular shape, structurally stable for the most diverse building applications, including use as hydraulic pipes;
- v. Excellent mechanical strength;
- vi. Almost total utility; the few residues generated by its use are biodegradable, easily reincorporating themselves into nature;
- vii. Smooth and attractive colored surface; and
- viii. Durability to within the normal life expectancy of conventional materials, relative to the environment conditions where it is used.

For large-scale use of bamboo as an economically viable and industrially feasible engineering material, systematic scientific study and complete statistical analyses concerning its propagation, planting, treatments and post-treatments, together with physical and mechanical characterization are necessary.

In certain Latin American countries such as Colombia and Brazil, there are small companies that are already able to provide bamboo stalk in differing diameters. Production of bamboo culms is increasing in Brazil, motivated together by the growing market and the Brazilian Association of Bamboo Producers (APROBAMBU). Bamboo, as a readily available construction material, will be a reality.

As with all vegetal materials, the physical and mechanical properties of whole bamboo culms are variable. Yet it remains possible to create reliable design criteria and employ industrial processes for economic use of bamboo at a large scale.

In Brazil, the first scientific studies on bamboo began in 1979 at the Department of Civil Engineering of the Pontifical Catholic University of Rio de Janeiro (PUC-Rio), under the direction of Prof. Khosrow Ghavami. Since then, several programs have been developed to investigate the use of bamboo and natural fibers (sisal, coconut, piaçava and cellulose bamboo pulp), as low environmental impact materials for use in construction.

In this chapter, general information about bamboo is presented together with results from biological, physical, mechanical, and structural (meso-micro) characteristic studies; for the purpose of engineering applications. Factors such as age, cutting time, curing and drying periods, and treatments against fungi and insects; all of which affect shelf life, are also necessary to take into account

Bamboo usage is widespread throughout the world, especially in Asian countries. Japan, China and India have all used this extraordinary plant for thousands of years. In certain regions, bamboo is considered sacred; such are the benefits it provides. In South America, Colombia stands out as the country that invests the most in the use of bamboo for buildings. In Brazil, bamboo has not yet received the attention it deserves; in addition to its agronomic and technological characteristics being little publicized, there is still an ideology associating the plant with poverty. Bamboo stakes and canes are already used in the rural environment as tutors for plants, bamboo also provides contours, fences, decks, feeders, mats, baskets, linings, soil protection, windbreaks, erosion control, charcoal, drainage, water conduction, food, and even fishing rods. It is known as “the plant of thousand uses”.

Figs. 1-4 present works that reveal the great potential of bamboo. Bamboo is exceptionally practical for removable/portable structures (Fig. 1), but also for permanent constructions. Fig. (2) shows a steakhouse in Colombia; Fig. (3) presents work by the Colombian Architect Simon Velez known as “The Bamboo Cathedral” in Pereira, Colombia; and in Fig. (4) an Indonesian schoolhouse is presented.



Fig. (1). Removable bamboo structures.



Fig. (2). Steakhouse in Villavicencio, Colombia.



Fig. (3). The Bamboo Cathedral:
(a) View during day; (b) Interior; (c) View at night.



Fig. (4). Schoolhouse in Indonesia; made with bamboo (Source: eficienciaenergetica.blogspot.com).

2. GENERALITIES CONCERNING BAMBOO

Bamboo is a giant grass, belonging to the family *Poaceae*, subfamily *Bambusoide*, and forming part of the order *Graminales*, in the class *Monocotyledoneae* a division of *Angiospermeae*. Native bamboo can be found on all of the continents excluding Europe and Antarctica; and it grows in tropical and subtropical zones of the Earth. According to Lopés [1], there are more than 1,600 species of bamboo in the world; 440 of them are native to the Americas, 1,000 species are from Asia and Oceania, and a smaller number of species originate in Africa.

2.1. Morphology

The external structure of the bamboo is formed by:

- i. Rhizomes and roots;
- ii. Culm;
- iii. Twigs;
- iv. Sheets; and
- v. Flowers and fruits.

2.1.1. Rhizomes and Roots

In the asexual reproduction of bamboo, the rhizome is the vital organ which also stores and transports nutrients. The rhizome can be viewed as an underground ecological factory, where each year brings new shoots. In accordance with rhizome morphology there are three major types of bamboo: Pachymorph, Leptomorph, and Metamorph, which can be seen in Fig. (5).

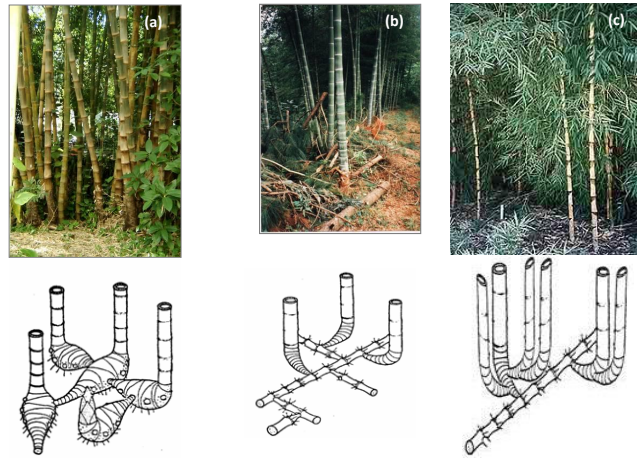


Fig. (5). Classification of bamboo by the type of rhizome: (a) Pachymorph; (b) Leptomorph; (c) Metamorph.

Pachymorph rhizomes are typical of tropical zones in the Americas, Asia, Africa, and Oceania. The pachymorph rhizome (Fig. 5a) is solid, curved, short and thick. Its internodes are wider with a maximum thickness, which in some cases is larger than that of the culm [2].

Leptomorph rhizomes, as presented in Fig. (5b), are long and cylindrical, and present smaller diameters than that of their corresponding stems.

Metamorph rhizomes being a transformational type between one and another, are neither fully leptomorph, nor pachymorph, Fig. (5c).

2.1.2. Culms

The stems or culms form the main aerial part of the plant. They are used in construction. The stem is born from the apex of the rhizome and presents a segmented stalk, (node and internode). The lengths of bamboo stems vary greatly with species. There are species with stems a few centimeters high, and others which exceed 30 meters. Figs. (6a), (6b), (6c) and (6d) represent *Guadua angustifolia* stem growth stages.

Stem growth occurs very quickly. The length increases a few centimeters (approximately 15 cm to 20 cm) per day; and high growth records of more than 1 meter in a single day have been reported.

When young, the bamboo shoots are a much appreciated food that is appreciated throughout the world.



Fig. (6). Stages of bamboo culms *Guadua angustifolia*.

The node is where branching originates. Internally, the node is represented by a horizontal solid plate of vascular bundles; the diaphragm. According to López [1], pachymorphs and leptomorphs have similar anatomical structures in the nodal region, and certain species of the pachymorph group develop dense roots around the nodal region in the lower part of the stem.

The internode (Fig. 7) is the section between two consecutive nodes. The wall of the internode can vary, from very thin to very thick. In American bamboos, the outer surface of the internode is completely smooth, yet may exhibit some roughness with a greater or lesser degree of wrinkling. The interior diameter decreases from the base towards the top.

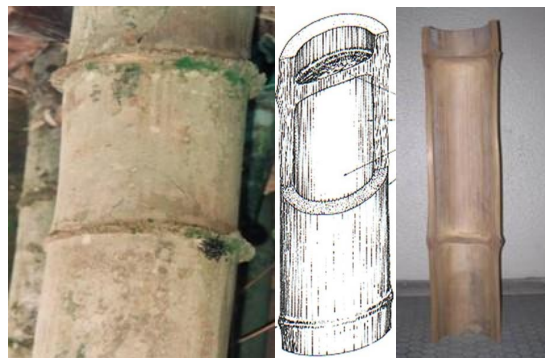


Fig. (7). Macroscopic profile of bamboo culm: internode.

2.1.3. Branches

The branches originate from the culms and alternate from side to side, from successive nodes. In some species, branches develop during the growth phase; in others, branches develop when a defined growth has been achieved. Some species have relatively large branches as presented in Fig. (8); while others present much smaller branches.

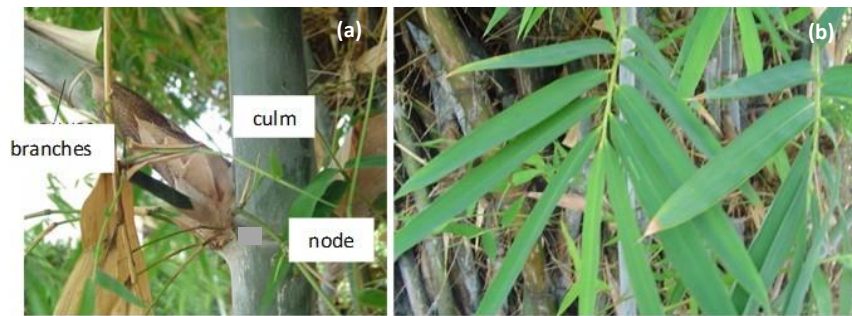


Fig. (8). Bamboo branches (a) and leaves (b).

2.1.4. Leaves

Bamboos have two types of leaves: those that grow at the ends of the branches and those that grow from the stem. The first type according to Fig. (8b), are the leaves themselves, which carry out photosynthesis. The second type, called stalk leaves, bracts or sheaths (Fig. 9), are born in the nodes, and protect the gems (parts of the plant that originate branches) from mechanical damage and insects. The inner face of the sheath is smooth and shiny, but when young, the outside is covered with irritating hairs with varied colors, such as white, brown, or black gray. The stalk leaf shape and geometry varies by species.

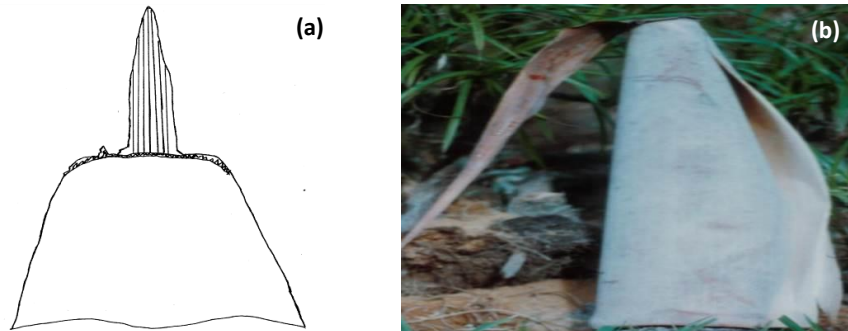


Fig. (9). *Dendrocalamus giganteus*: (a) bamboo leaf (b) bamboo sheath/stalk leaf.

2.1.5. Flowers and Fruits

Some bamboo species, such as *Bambusa vulgaris*, never bloom. In others, flowering occurs in more or less regular periods, (varying from 3 to 160 years). Depending on the species, blooms can weaken the plant, determining death of both stems and branches. According to Salgado and Azzini [3], if a new stem arises from a rhizome that had its stem blooming, this new stem produces flowers in its first year of growth and then usually dies. According to the same authors there are three basic types of flowering: annual, sporadic, and gregarious. Annual flowering occurs on herbaceous bamboos, which are of little economic

importance and not used in engineering. Sporadic and gregarious flowering occurs in woody bamboos. Sporadic flowering occurs in isolated stems originating from a shared clump. Gregarious flowering occurs when all of the stems of a clump or bush bloom; the death of the stem and also of the rhizome follows.

Bamboo flowers turn into seeds whose aspect is presented in Fig. (10).



Fig. (10). Bamboo seeds.

3. HOW TO GET CULMS TO CONSTRUCTION

To get adequate culms for engineering purposes the following steps are necessary:

- i. Selection;
- ii. Cutting;
- iii. Curing;
- iv. Drying; and
- v. Immunization treatments.

3.1. Selection

For durable constructions, choosing suitable culms is critical. The first aspect to observe is the age of the bamboo: if very young, it may not yet have developed its strength and may also be more susceptible to attack by insects and fungi; if very old, it may already present weakened mechanical properties.

The ideal age for picking culms is from three to seven years, varying by species. In the case of rational exploitation of bamboo plantations, as is already the case in many parts of Colombia and Brazil, the age of the material is well known and it is properly cut at the appropriate time. When the bamboo must be obtained without knowledge of its age, it is necessary to observe certain differences between green and mature shoots.

Green culms present a more intense color, a waxy surface, and bracts in the nodes, with few or no branches, as seen in Fig. (11a).

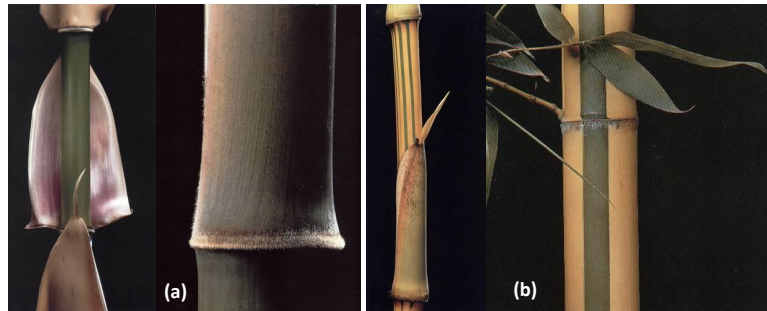


Fig. (11). Aspects of bamboo culms: (a) young, (b) mature [4].

Mature culms present less intense color, a hard surface, without bracts, with some branches in the nodes, as indicated in Fig. (11b).

3.2. Cutting

Cutting should be done carefully to avoid damaging the bamboo. The use of an electric saw is preferable. In the bamboo has not been properly handled, the cutting operation is very laborious, especially if the proper equipment is not available. In pachymorph species, the mature culms are usually inside the clump, which makes access more difficult.

The cut should be made at the height of the second node, just above it, and avoiding any possibility of accumulation of water inside the piece of stem that remains in the soil.

3.3. Curing

The curing process minimizes the amount of sap inside the culms. The sap attracts insects and it is therefore preferable to reduce its quantity.

If time is available, the cure can be performed at the clump itself: cutting the culm and letting it rest on a rock for the sap to flow out. This process is beneficial because the bamboo is losing sap and humidity in its own environment, which is not too dry; fast drying is avoided, reducing the risk of cracking.

Two to three weeks are recommended for curing at the clump. However, in certain species very susceptible to insect attack, as in the case of *Bambusa Vulgaris*, this may be enough time for an attack. It is often prudent to leave the stalks in the woods for only a few days, or to transport them immediately after cutting for immunization treatments.

Another way to extract the sap from the stalks is by immersion. When immersed

in water, the stems are penetrated, and the sap dissolves into the water. The time required is approximately 2 to 4 weeks; (be careful to change the water in the middle of the treatment), as a rather unpleasant smell can be produced. In this process, keeping the stems submerged can also be difficult, since they are hollow and of lower density than water, and the general tendency is to float. A system that secures complete immersion must be used. However, using these procedures to extract the sap from the stalks is no guarantee that the insects will not attack the bamboo.

Another curing process is heat: part of the sap is expelled from the stem by exposure to high temperatures. In this case, curing and drying are done at the same time. The process is delicate and must be done carefully because of the risks of cracking in the stems.

3.4. Drying

Drying reduces the stem humidity to that in equilibrium with the atmosphere. In areas with 70% to 80% relative humidity, after drying the culms will have a moisture content of 12% to 16%. In low humidity environments it can reach 8% to 12%.

The drying process is of great importance to the quality of the culms. If it is too fast, longitudinal cracks may occur that detract from the aesthetics and durability of the material. Drying should not be done in the sun, yet protected from atmospheric phenomena.

Another form of drying is with fire, or using a point source of heat such as a torch. In this process, low heat is important, as it can provide a shiny and strong surface. However, since it must be applied to each and every culm, this method becomes time consuming and laborious.

Greenhouses are a very effective means of drying bamboo, as is also done with other woods. And there are greenhouses that take advantage of the sun's heat during the day.

3.5. Immunization Treatments

Curing and drying processes alone are not enough to extract all of the culm components from which insects feed. Thus, as in the case of wood, it is necessary to apply treatments to prevent predators. Some species, such as *Bambusa vulgaris*, are much more susceptible to attack than others such as *Dendrocalamus giganteus*.

In Brazil, the principal bamboo predator insect is the coleopter *Dinoderus*

minutus, shown in Fig. (15). The 2 to 3 mm long insect attacks only mature bamboo. The mechanism of attack is as follows: the adult insect pierces the culm and lays its eggs inside; when they hatch, the larvae feed on the plant, destroying it completely, as seen in Fig. (12). Once reaching adulthood, the insects fly to another host, restarting the process.



Fig. (12). The insect *Dinoderus minutus* and the resulting damaged bamboo.

Several immunization treatments can be adopted to preserve bamboo. Wood immunization methods may also be used. Natural products, such as that extracted from the Nin plant, may succeed in killing the insect, and yet present limited residual effect. After some time, the insects may then reappear to attack the treated culms.

In the literature, several products are indicated for use to treat bamboo, usually by immersion in aqueous solution, for example:

- i. Boric acid;
- ii. Borax (Boron salt);
- iii. Copper sulphate;
- iv. Acetic acid;
- v. Zinc chloride; and
- vi. Sodium dichromate.

Tests performed by Barbosa in 1988 at the Federal University of Paraíba, in Campina Grande revealed good results from treating culms using immersion in diesel fuel. Painting or sprinkling of the product alone was insufficient for definitive protection. However, this treatment product is polluting and not recommended since it emits toxic gases. Of the aforementioned, boric acid and borax, often used together (diluted in water by about 3% or 4% each) are the less aggressive products.

Another treatment involves smoke treating the bamboo by introducing it into a compartment with a small air outlet that presents fire and smoke beneath the

culms. The smoke remains impregnated in the culms (Fig. 13) and the insects leave.



Fig. (13). Industrial smoke treating of culms.

4. PHYSICAL PROPERTIES

The physical properties of bamboo culm such as length, distance between the nodes, diameter, wall thickness, specific weight, *etc.*, depend on many factors such as:

- i. Species;
- ii. Soil quality, temperature, relative humidity of the local environment, solar radiation, altitude, spacing between clumps, rainfall, *etc.*;
- iii. Management of bamboo plantation; and
- iv. Location along the culm.

4.1. Inter-nodal Distance, Outside Diameter, Wall Thickness

At PUC-Rio, Ghavami and Marinho [5] investigated the physical properties of certain bamboo species. External diameters, the inter-nodal lengths, and wall thicknesses were measured. In order to obtain the wall thicknesses, the device in Fig. (14c) was developed.

The inter-nodes were numbered from the base to the top, defining a coordinate system (Fig. 14) and their lengths were measured with precision. The external diameter of each inter-node was determined with a pachymeter.

From the values obtained for the external diameters (D), wall thickness (t) and

inter-nodal length (l), and for the respective numbers of internodes (n), a law that relates inter-nodal length variation to stem height can be obtained.

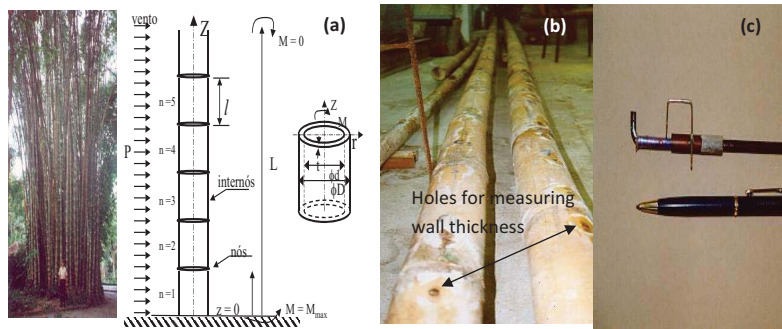


Fig. (14). (a) Coordinate system, (b) position of the holes and (c) apparatus for measuring the wall thickness of the bamboo culm.

Curves representing the variation of the length of the internodes of the entire bamboo stem for the species *Dendrocalamus giganteus*, *Phyllostachys heterocycla pubescens* (Mosó), *Phyllostachys bambusoides* (Matake), *Guadua angustifolia* in São Paulo, and *Guadua tigoara* and *Bambusa vulgaris* in Rio de Janeiro [6], are presented in Fig. (15). A well-defined behavior for all of the studied species can be seen: in the basal parts, they are shorter, in the central part of the culm, the values reach a maximum; and in the upper parts they decrease.

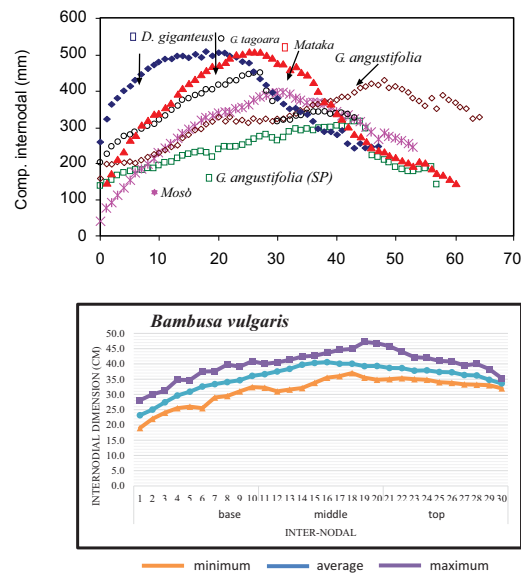


Fig. (15). Variation of the inter-nodal distance along the culm.

In Fig. (16) and Fig. (17), it can be seen that the wall thickness of the bamboo culm decreases as it moves from base to top.

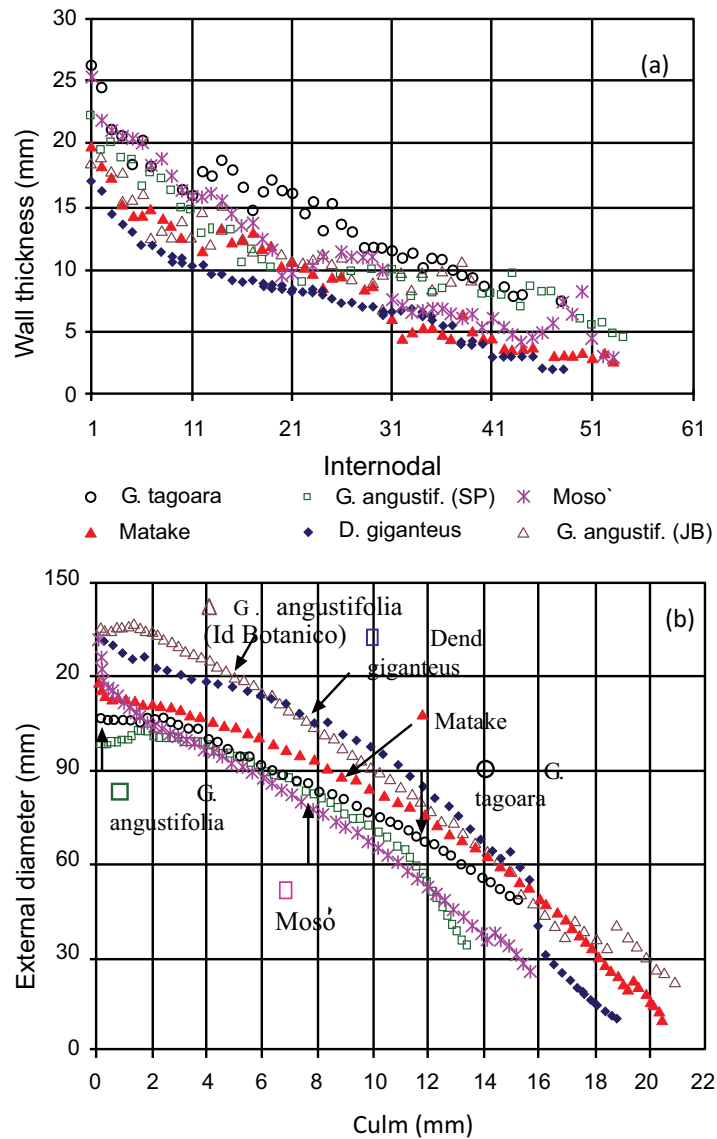


Fig. (16). (a) Variation of the wall thickness *versus* inter-nodal and (b) external diameter along the culm.

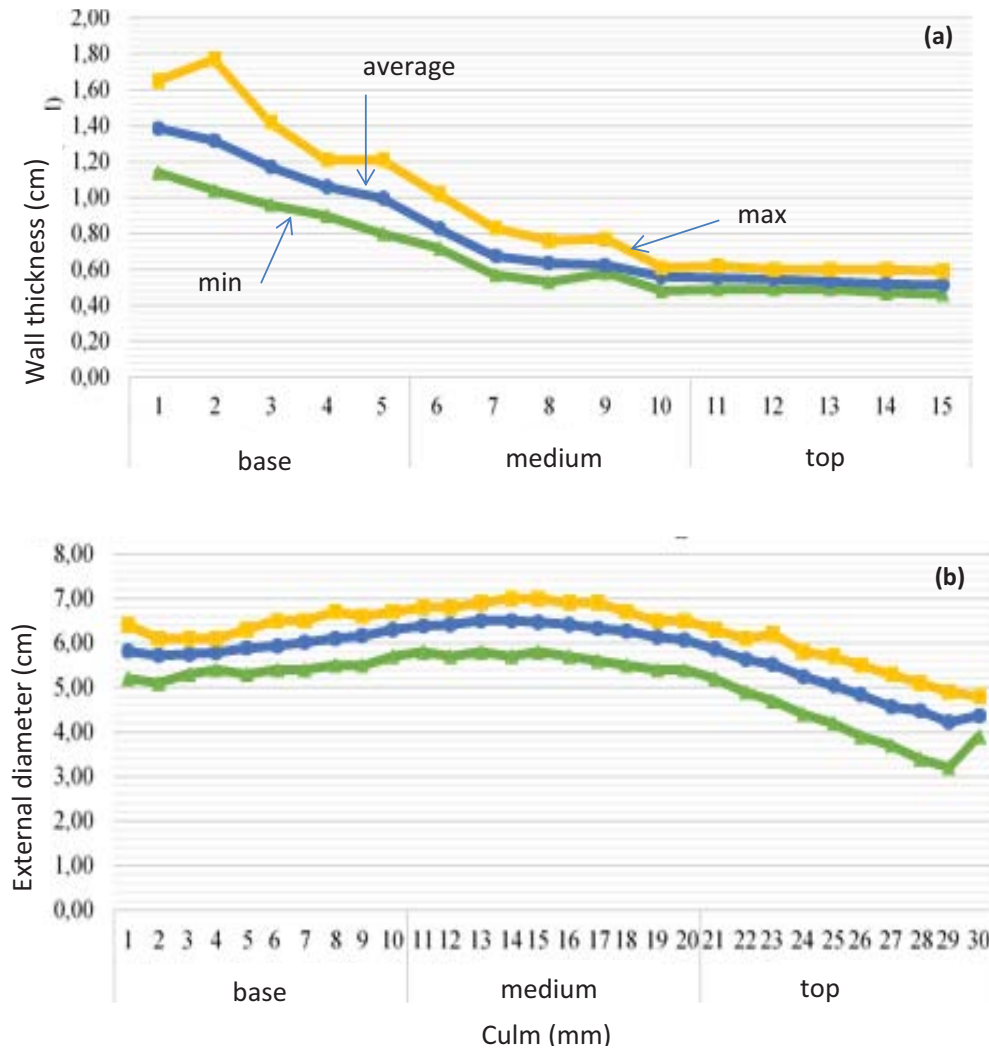


Fig. (17). In case of *Bambusa vulgaris*. (a) Variation of the wall thickness *versus* inter-nodal, and (b) external diameter along the culm.

The relationship between external diameter and culm inter-nodal number is presented in Fig. (18). The external diameter exhibits a nearly linear behavior, with values decreasing from the base to the top that give the culm a cone trunk-like appearance.



Fig. (18). Culms: (a) *Dendrocalamus giganteus* (Brazil), and (b) *Guadua* (Colômbia).

Table 1 shows the culm length, inter-nodal length, external diameter, and wall thickness values of the studied bamboos. The culms were divided into three (more or less) equal parts: base, intermediate, and top. The average value is indicated in each part and in the total height. A significant variation by species for these physical properties was observed.

It should be noted that the bamboo species *Dendrocalamus giganteus* (Fig. 18a) presents an average height of 22.3 m. However, there are culms that surpass 30 m. Diameters in the lower third of the culm are superior to 10 cm. This is an average value, as they can exceed 15 cm. Wall thickness can reach 1.5 cm. The culms are very linear, making them tubular construction elements of great potential.

Guadua bamboos (Fig. 18b) also present straight culms and very good properties for construction. However, those of the *vulgaris* species present certain drawbacks, such as the lack of stalk linearity, high susceptibility to insect attack, and little mechanical resistance.

Table 1. Physical properties of bamboos studied at PUC-Rio.

Species	L (m)	Inter-nodal Length (m)				External Diameter (cm)				Wall Thickness (mm)			
		Base	Center	Top	Mean	Base	Center	Top	Mean	Base	Center	Top	Mean
<i>Bambusa multiplex</i> (green - RJ)	3.0	-	-	-	0.45	2.5	-	1.5	2.0	4.0	-	3.0	3.5
<i>Bambusa multiplex</i> (green-emerald - RJ)	7.5	-	-	-	0.45	3.5	-	2.75	3.12	4.5	-	3.25	3.5
<i>Bambusa tuldoide</i> (RJ)	8.0	-	-	-	0.4	3.75	-	2.5	3.5	7.0	-	4.5	5.5

(Table 1) cont.....

Species	L (m)	Inter-nodal Length (m)				External Diameter (cm)				Wall Thickness (mm)			
		Base	Center	Top	Mean	Base	Center	Top	Mean	Base	Center	Top	Mean
<i>Guadua superha</i> (RJ)	9.0	-	-	-	0.4	11.0	-	7.15	9.0	9.5	-	6.5	7.5
<i>Bambusa vulgaris</i>	10.0	-	-	-	0.33	7.5	-	5.8	6.95	10.0	-	5.5	7.5
<i>Bambusa Vulgaris</i> Schard (RJ)	13.0	-	-	-	0.34	8.0	-	6.0	7.33	9.66	-	8.33	8.83
<i>Dendrocalamus giganteus</i> (RJ, PB)	22.3	0.49	0.54	0.41	0.47	13.4	11.0	7.50	10.68	14.4	9.66	6.59	10.22
<i>Mosó</i> (SP)	15.7	0.22	0.38	0.29	0.39	10.7	7.52	4.10	7.86	17.0	8.79	5.33	11.17
<i>Matake</i> (SP)	20.5	0.34	0.48	0.26	0.33	10.8	7.94	3.01	7.02	14.5	7.66	3.83	8.93
<i>Guadua angustifolia</i> (méd.RJ,SP)	18.2	0.23	0.32	0.29	0.27	11.3	8.58	4.30	8.51	15.5	10.1	8.23	11.53
<i>Guadua tigoara</i> (SP)	15.2	0.32	0.42	0.34	0.34	10.3	8.57	6.19	8.37	19.3	14.7	9.87	14.74

4.2. Water Absorption

Being a vegetal material, bamboo absorbs moisture easily if it remains in contact with water. Absorption can be reduced through surface treatments. Table 2, obtained at the Federal University of Paraíba, shows the results of bamboo water absorption for two species, taken after the specimens were dried in an oven. It was observed that even after three days of immersion, the materials continue to absorb water, and at four days, the absorption reached more than 30%. It was also noted that the species *Bambusa vulgaris* absorbed more water than *Dendrocalamus giganteus*.

To reduce absorption, petroleum based products (asphalt, tar, and industrial waterproofing) were tested. In Table 2, the different performances for the treatments can be seen. Absorption can be reduced, but it can hardly be eliminated.

A consequence of water absorption is dimensional variation: when bamboo absorbs water, its dimension increase; when losing water dimension decrease. Such variations also depend on the direction in which you are measuring. In Table 3, it is seen that, in the longitudinal direction, dimensional variation is minimal. In the radial direction, the increase is on the order of 6%. It should be noted that, despite absorbing less water, the bamboo of the species

Dendrocalamus giganteus presents larger dimensional variations than those of *Bambusa vulgaris*. This can be explained by the fact that *Dendrocalamus giganteus* presents a more compact microstructure, and thus capillary tensions are larger, causing greater expansion of the material when water penetrates. Moisture in bamboo diminishes its valuable mechanical properties.

Table 2. Percentage water absorption for two species of bamboo; *in natura* and treated.

Species	Treatment Product	Immersion Time			
		24 h	48 h	72 h	96 h
<i>Dendrocalamus giganteus</i>	-	21.2	25.0	27.7	31.7
	A	11.0	15.2	16.1	18.5
	B	9.9	14.0	18.5	21.4
	C	4.4	6.0	7.7	10.3
	D	2.4	5.0	7.7	10.0
<i>Bambusa vulgaris</i>	-	25.7	30.2	32.4	34.3
	A	15.9	18.9	20.9	22.3
	B	14.6	20.0	23.6	27.3
	C	3.8	7.2	9.4	10.9
	D	8.1	17.5	22.1	25.6

Table 3. Dimensional variations of bamboo specimens after immersion in water.

Species	Direction	Dimensional Variations (%)				
		24 h	48 h	72 h	96 h	168 h
<i>Dendrocalamus giganteus</i>	circumferential	1.6	2.8	2.8	2.8	3.3
	longitudinal	0.0	0.3	0.3	0.3	0.5
	radial	2.2	4.8	5.7	5.9	6.6
<i>Bambusa vulgaris</i>	circumferential	3.0	3.2	3.5	3.6	3.7
	longitudinal	0.4	0.4	0.4	0.4	0.4
	radial	3.8	4.2	4.7	5.3	5.6

4.3. Specific Mass

The specific mass of bamboo stem walls is lower than that of water, ranging from 0.7 kg/dm³ to 0.9 kg/dm³ in the species most suitable for construction.

5. MECHANICAL PROPERTIES

The mechanical properties of bamboo vary along the same parameters that

interfere with its physical properties. As the search for materials with lower environmental impact is spreading, it is necessary that guidelines are created for their safe use, and also their acceptance in the technical environment. Based on results obtained in bamboo research during the last three decades in various parts of the world, including Brazil, it was possible to create the first standards for the use of bamboo in engineering works.

The International Network for Bamboo and Rattan, INBAR (2000), of which Ghavami was a senior member in the Bamboo Standards Committee, developed proposals that were adopted by the International Organization for Standardization. One of them deals with design of bamboo structures, ISO 22156 [7], while the other, ISO 22157 [8] refers to tests determining the physical and mechanical properties of bamboo.

Since 2010, Colombia was able to insert a standards annex related to the most widespread bamboo in that country, *Guadua* [9], ICONTEC for design of wooden structures. Ecuador and Peru have also recognized this bamboo standard.

In Brazil, the Brazilian Bamboo Network has prepared a proposal for the Brazilian Association for Standardization, and presently a committee of specialists is preparing a text concerning “Design of Bamboo Structures”.

The mechanical properties of bamboo of major interest for engineering are: tensile strength parallel to the fibers, compressive strength parallel to the fibers and shear strength parallel to the fibers. Flexural strength may also be of interest, but more often in bending elements, it is deformation that is most important.

5.1. Compressive Strength

Bamboo tensile strength parallel to the fibers is high, reaching around 300 MPa. In bamboo standards, the specimen with the geometry indicated in Fig. (19) is suggested. The thickness can be from 3 mm to almost the thickness of the stem wall.

Since bamboo is very strong, it is convenient to glue an aluminum plate on each end. To avoid crushing which the claws of the test machine can cause in these regions, epoxy-based glue should be used.

Resistance is calculated from the maximum force value read on the test machine divided by the cross-sectional area of the center of the specimen.

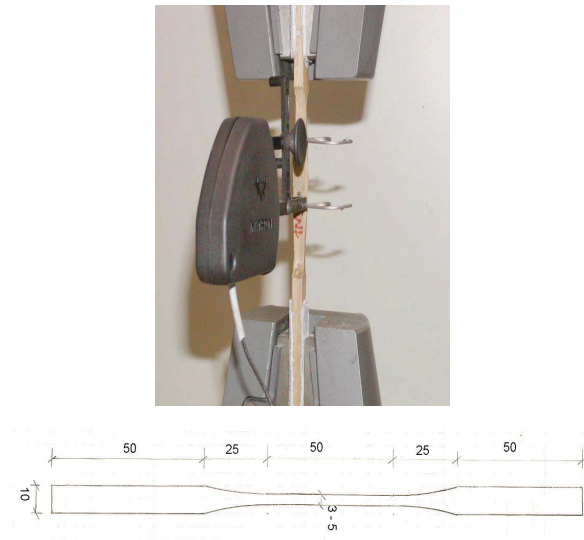


Fig. (19). Dimensions of the specimen are indicated by INBAR for test of tensile strength parallel to the bamboo fibers using the test in progress.

Fig. (20) shows typical curves related to stress-strain behavior. It should be noted that the behavior is almost linear until rupture. When the specimen includes the portion of the knot at its center, the strength and slope of the stress-strain curve decrease.

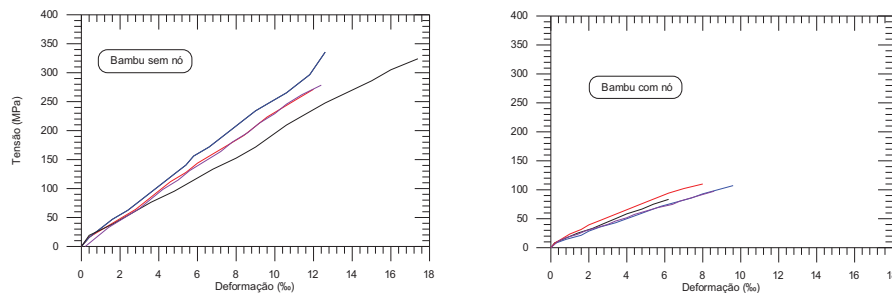


Fig. (20). Typical tensile stress-strain curves of bamboo (with and without knot), to maximum load [10].

5.2. Compressive Strength Parallel to Fibers

The compressive strength is generally between 20 MPa and 120 MPa; 30% lower than the tensile strength, and varies greatly with species.

The specimen recommended by ISO 2004b and the proposed Brazilian standard is a cylinder with a height equal to the diameter, as presented in Fig. (21).



Fig. (21). Dimensions of the specimen are indicated by INBAR for compressive strength parallel to the bamboo fibers, and by the test in progress.

The resistance is given by the maximum force obtained on the test equipment divided by the cross-sectional area of the cylindrical specimen, which can be determined by the expression:

$$A = \pi \times t (D - t) \quad (\text{Eq 1})$$

Where: A is cross-sectional area; t is the wall thickness; and D is the external diameter.

In Fig. (22), typical stress-strain curves can be seen for non-knotted specimens to the maximum load value, obtained from compression testing. Even if the specimen presents a node in its center, the appearance of the diagrams obtained is very similar. Here also, linear behavior is observed for the material up to the maximum stress.

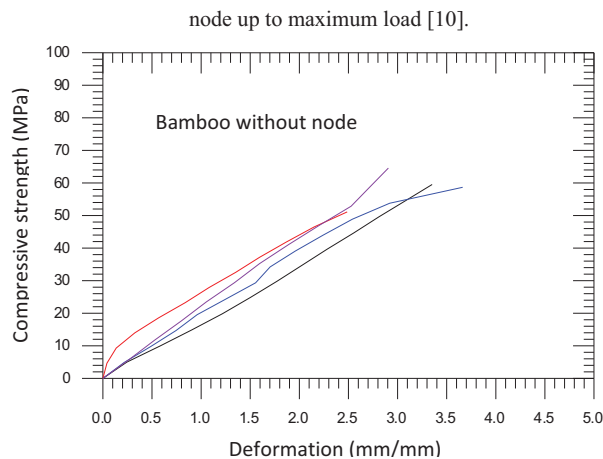


Fig. (22). Typical compression-deformation stress curves for bamboo with and without node up to maximum load [10].

5.3. Shear Strength Parallel to Fibers

In bamboo structural element connections, pins can be used. In order to correctly design the connections, it is necessary to determine shear strength in parallel with the fibers, that is, shear strength in the longitudinal direction of the stem. A test specimen as suggested by Ghavami and Marinho [5], is presented in Fig. (23). There are two notches of 5 mm apart, 60 mm apart between them. At the end of the test specimen, it is advisable to glue an aluminum plate.

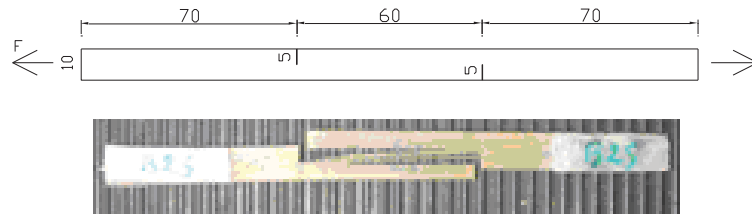


Fig. (23). Dimensions of test specimen indicated for testing of shear strength (parallel to bamboo fibers), and test specimen after test.

The shear strength is calculated by dividing the maximum load applied to the specimen by the area of the shear surface. Within an order of magnitude, it can be said to fall between 2 MPa and 8 MPa, and may even reach 10 MPa.

5.4. Summary of Mechanical Properties in Tension and Compression Parallel to Fibers

Table 4 shows the tensile and compressive strengths, and the respective modulus of elasticity of certain bamboo species studied at PUC-Rio. Specimens extracted from mature culms were used, and variations in properties (according to species) were noted. Other studies may indicate differing values since factors relating to location and environmental conditions can interfere significantly. When it is desired to properly design and build with bamboo, the realization of tests is important.

It should be remembered that the values in were obtained with dried test specimens (moisture in equilibrium with the atmosphere), at about 12% to 15%. As the material presents higher moisture, resistance decreases. In design standards for bamboo structures, this is taken into account.

6. FUTURE PERSPECTIVES

On a planet in search of reduced energy consumption and reduced pollutant emissions, bamboo, an intelligent plant, is undoubtedly a material of the future. The emergence of commercial bamboo plantations raising construction suitable

species is already happening in Brazil (as in Colombia). The Brazilian Bamboo Network (RBB) brings together experts from all areas of the plant's production chain. The Association of Bamboo Producers (APROBAMBU) also increases the prospects of bamboo becoming a more easily available construction material in the country. The durability of construction with bamboo can be assured through correct handling of the culms and through appropriate applications. A good building design, ensuring no exposure of the material to direct sunlight or humidity, is crucial for long lifespan.

Table 4. Mechanical properties of bamboo species studied at PUC- Rio.

Specie/Place		Tension				Compression			
		Resistance (MPa)		Modulus of Elasticity E_t (GPa)		Resistance (MPa)		Modulus of Elasticity E_c (GPa)	
		with node	without node	with node	without node	with node	without node	with node	without node
<i>Bambusa multiplex</i> Disticha (RJ)*	Base	68.8	98.0	11.11	14.08	20.60	30.00	3.05	4.15
	Center	-	-	-	-	-	-	-	-
	Top	79.8	108.4	11.95	14.92	20.00	26.50	3.54	4.27
	Mean	74.3	103.2	11.53	14.50	20.30	28.25	3.29	4.21
<i>Bambusa tuldoide</i> (RJ)*	Base	112.0	140.5	9.99	12.66	30.20	37.80	2.97	3.24
	Center	-	-	-	-	-	-	-	-
	Top	95.80	98.0	8.55	11.19	30.00	38.3	2.83	2.78
	Mean	103.9	119.2	9.27	11.92	30.10	38.05	2.90	3.01
<i>Guadua superba</i> (RJ)*	Base	108.8	142.6	8.33	10.48	36.40	50.60	2.46	3.12
	Center	-	-	-	-	-	-	-	-
	Top	115.8	151.0	9.42	11.83	35.00	45.00	2.83	3.55
	Mean	112.3	146.8	8.87	11.15	35.70	47.80	2.64	3.33
<i>Bambusa vulgaris</i> Schard (RJ)*	Base	131.6	176.4	8.46	10.02	37.50	53.00	2.59	2.86
	Center	106.1	153.5	8.50	10.22	39.50	46.00	2.36	3.19
	Top	145.6	182.0	9.45	12.67	42.00	59.00	2.80	3.67
	Mean	127.7	170.6	8.80	10.97	39.66	52.66	2.58	3.24
<i>Dendrocallamus giganteus</i> (RJ)*/ **	Base	106.8	147.0	12.98	19.11	58.66	56.61	12.07	15.29
	Center	143.6	188.1	16.73	15.70	53.96	63.77	15.15	11.26
	Top	114.0	157.6	13.44	10.71	54.04	72.87	9.79	10.41
	Mean	121.5	164.2	14.38	15.17	55.55	64.42	12.34	12.32

The culm's low weight and high resistance recommends its use in space trusses, as presented in Fig. (24) [11]. Yet it remains important in such applications to develop adequately interlocking connections.

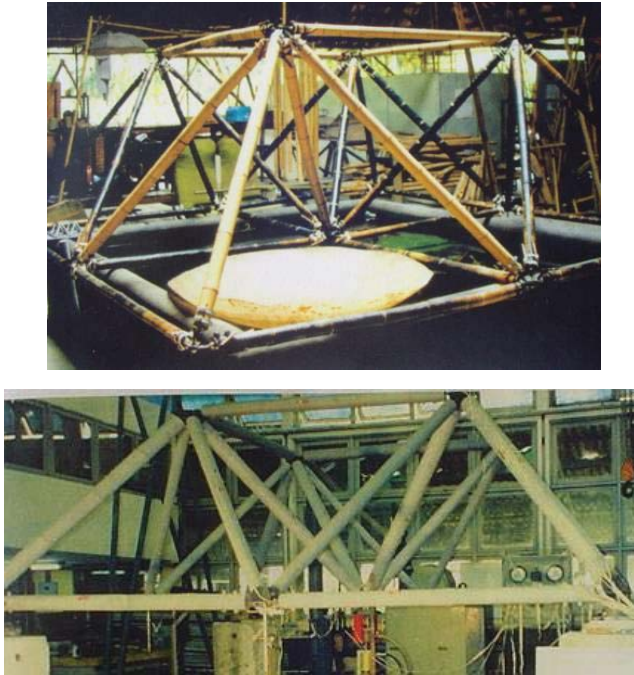


Fig. (24). Bamboo space truss conceived at PUC-Rio.

The versatility of the bamboo is indisputable, and the emergence of bamboo based construction technologies, such as those developed by Cardoso Jr., Sartori and Silva [12], (in the scope of engineering) is occupying greater spaces. In their study, bamboo became the internal reinforcement for panels; lined with a light mortar (based on cement, lime, and residues of rubbers, EPS, and even shredded bamboo itself) (Fig. 25), which lowered prefabrication and construction times. This type of technology can be used to generate community jobs and income. Since the material demand for bamboo culms in home construction is relatively large, and there is a need for species that have the proper diameter for this type of application, commercial plantations are needed.

Bamboo can be used as concrete reinforcement in small beams [5]. Rods extracted from the culm, two to three centimeters wide, can work as longitudinal reinforcement. Because the bamboo presents a modulus of elasticity much lower than steel, the beams have higher deformation. In Fig. (26) [13], preparation of beam reinforcement and testing can be seen. In this study, the enormous

deformation capacity can be perceived.



Fig. (25). Construction system developed at the Bambu Institute, Maceió-AL [12].



Fig. (26). Bamboo as longitudinal reinforcement in beams, being tested at the University of Western Paraná, Cascavel-PR.

Bamboo culms can also be used in concrete pillars, functioning as longitudinal reinforcement [14]. In Fig. (27), a surface treatment (epoxy-based adhesive) was used to improve adhesion. Bamboo can give ductility to the whole structure, improving the structural behavior of the pillar.

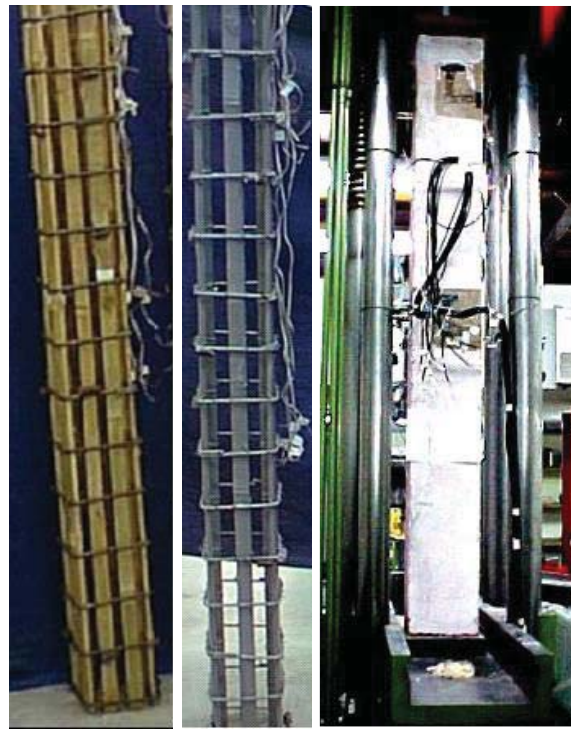


Fig. (27). Longitudinal (left), reinforcement with treatment (center), and pillar being tested (right), at PUC-Rio.

Another very interesting use of bamboo is in permanent mold slabs. The culms are cut in half and placed in parallel with each other; (Fig. 28) [15], upon receiving a layer of concrete, the bamboo is transformed into a slab. The bamboo in the platform acts simultaneously as both tensile reinforcement and mold. The nodes play the role of connectors, allowing joint deformation of the two materials. In order to improve the interaction between concrete and bamboo, an epoxy-based adhesive can be applied. By casting the concrete layer with the adhesive (being plastic), a very good bond is formed between the two materials. Tests performed at the Federal University of Paraíba on 3 m open slabs and at PUC-Rio at 3.5 m presented excellent structural behavior. It supported the service loads loosely and exhibited remarkable ductility with high deformation before breakage. The lower face of the slabs, which serves as the ceiling for the lower floor, can receive treatment with varnishes and obtain a beautiful effect. For this it would be necessary that the stems be linear and of approximately the same diameter.



Fig. (28). Permanent bamboo shoot slab.

6.1. Impregnation of Bamboo with Polymeric Resins

By combining bamboo and polymeric resin a new material can be generated. Analyzing the microstructure of bamboo, it can be seen that it is a composite material, with fibers immersed in a lignin matrix (Fig. 29).

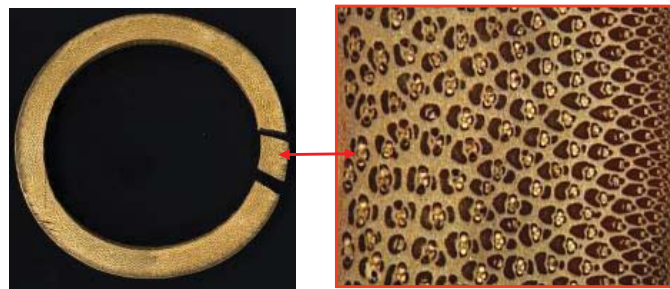


Fig. (29). Transversal view of bamboo section.

The fiber presents sap-conducting vessels that serve to feed the plant (Fig. 30). The idea is to fill the vessels with polymeric resins, which can reach further than 200 μm .

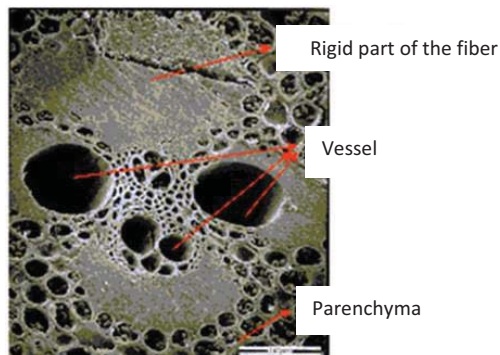


Fig. 30. Transversal view of bamboo fiber.

The first studies used (80% styrene + 20% methyl methacrylate) resin and equipment that pushed the resin into the stem under pressure. Success was only achieved using small pieces of culms (Fig. 31). When nodes are present, difficulties appear. The specie used was *Bambusa vulgaris* [16].



Fig. (31). Impregnated bamboo stem.

In a second phase, more appropriate resins were studied by Reres Ortiz [17] and after many tests it was concluded that pre-treatment with glutaraldehyde followed by impregnation with poly(styrene-co-methyl methacrylate) would be successful. A small sample vacuum process was used, according to ASTM 143-09 “Standard test methods for small clear specimens of timber”.

In Fig. (32), small sample stress strain curves for bamboo impregnated with the products described above are presented. Average value compression strength went from 56 MPa, in natural bamboo to 85 MPa, in impregnated bamboo; a gain of about 50%.

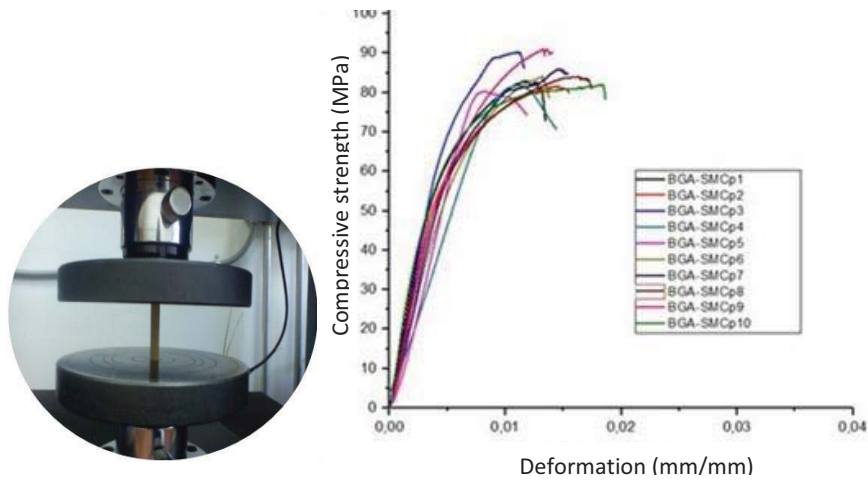


Fig. (32). Small sample compression testing and stress strain curves for impregnated bamboo.

Fig. (33) shows bend testing and the curves obtained from impregnated bamboo, from about 100 MPa to 118 MPa. The modulus of elasticity also increased with the partial filling of voids with resin.

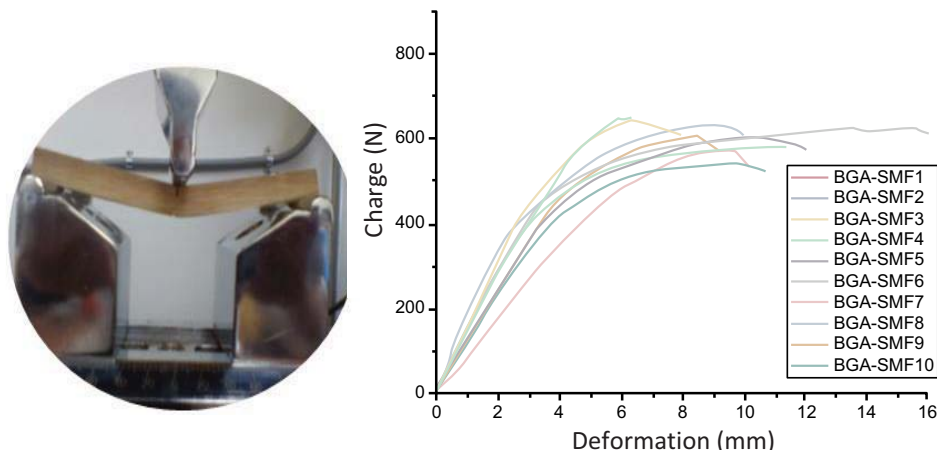


Fig. (33). Small sample bend testing and load-arrow curves for impregnated bamboo.

In Fig. (34), cuts showing bamboo vessels can be seen. On the left, natural bamboo, on the right an impregnated sample. It may be noted that the fill is not perfect; which suggests that more research is needed.

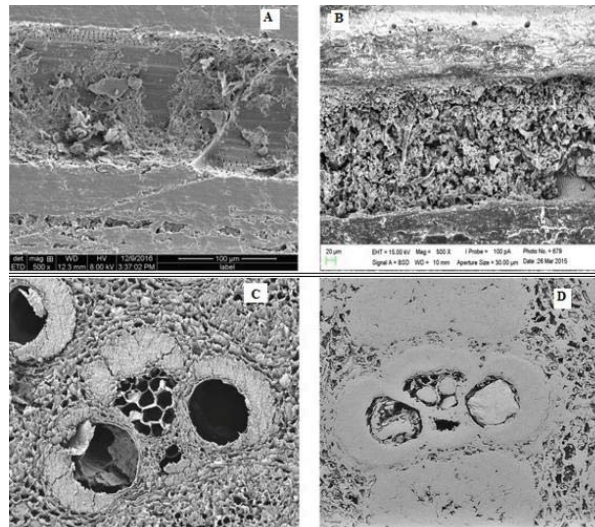


Fig. (34). Microscopy of bamboo: (a) longitudinal section of natural bamboo; (b) longitudinal section of impregnated bamboo; (c) cross section of natural bamboo fiber; (d) cross section of impregnated bamboo fiber.

A beneficial effect of bamboo impregnation is immunization against insects. Testing was done over a period of six months, exposing bamboo in its natural and impregnated states to the insect *Dinoderus minutus*. In a short time, the natural bamboo was completely deteriorated, whereas the impregnated bamboo suffered no attack (Fig. 35).



Fig. (35). Impregnated bamboo: immune to insects.

Impregnation can improve bamboo's properties but presents difficulties. Further investigations are needed to develop long culm impregnation.

CONSENT FOR PUBLICATION

Not applicable.

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Declared none.

CONFLICT OF INTEREST

The authors confirm that this chapter contents have no conflict of interest.

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Frontiers in Bio-Inspired Mineralization: Addressing Mimesis of Four-Dimensional, Hierarchical, and Nonclassical Growth Characteristics of Biominerals

Stephan E. Wolf^{1,2,*}, Martina Schübler¹, Corinna F. Böhm¹ and Benedikt Demmert¹

¹ Department of Materials Science and Engineering, Institute of Glass and Ceramics (WW3), Friedrich-Alexander-University Erlangen-Nuremberg, Martensstrasse 5, 91058 Erlangen, Germany

² Interdisciplinary Center for Functional Particle Systems (FPS), Friedrich-Alexander University Erlangen-Nürnberg (FAU), Haberstrasse 9a, 91058 Erlangen, Germany

Abstract: Biominerals are structures essential to their host organism, for which they provide varying functions and features. Through evolutionary optimization, they present sublime material properties as yet unparalleled in anthropogenically created materials. Formed at ambient temperatures from benign materials, the underlying formation processes and mechanisms still challenge our understanding. In this essay, we identify three key challenges which must be overcome to successfully emulate advanced biomimesis of ceramic materials. As frontiers singled out from the various challenges involved in mimicking biomineralization *in vitro*, three fundamental lines of research are represented: (i) temporal control of mineralization, (ii) spatial control of mineralization by self-organizing scaffolds and, finally, (iii) control of mineralization by nonclassical crystallization and thus unconventional mechanisms which are not yet part of the pertinent physicochemical canon. We expect that by mastering these aspects, the discipline of bio-inspired mineralization will take us far beyond where we are today.

Keywords: Biomineral, Bio-Inspired Mineralization, Hierarchy, Nonclassical Crystallization.

* Corresponding author Stephan E. Wolf: Institute of Glass and Ceramics (WW3), Department of Materials Science and Engineering, Friedrich-Alexander-University Erlangen-Nuremberg, Martensstrasse 5, 91058 Erlangen, Germany; Interdisciplinary Center for Functional Particle Systems (FPS), Friedrich-Alexander University Erlangen-Nürnberg (FAU), Haberstrasse 9a, 91058 Erlangen, Germany; Tel: +4991318527565; E-mail: stephan.e.wolf@fau.de

1. INTRODUCTION

Biomaterials are inorganic yet biogenic solid-state materials, *i.e.* bioceramics. They are used by a variety of organisms as sensors, tools, skeletons, weapons, or protections against predators [1 - 5]. Although often made from benign materials such as calcium carbonate or calcium phosphate, they present remarkable features, excelling man-made materials in structural complexity and performance. The source of such inventiveness is the evolutionary optimization process, *i.e.* inheritance of genotypes affected by fortuitous variations combined with selection of those individuals which are better adapted against external threats. In a sense, their structural plurality represents a library of solutions which addresses threats imposed by the environment that have raised the evolutionary pressure on the respective species. However, evolution is not a convergence to a given, pre-determined, selected objective, *i.e.* a telos (τέλος Greek: target). Rather evolution is a non-teleological search for sufficient adaptation and optimization against current external threats. With regard to man-made materials, though evolution has been an excellent teacher for designing material properties; biomimetic approaches may yet provide further profit from two different advantageous aspects. First, thousands of millions of years have allowed nature to develop and extensively test exceptional solutions – an advantage often discussed in terms of biomimetic design. Second, evolution proceeds as a non-guided, or non-teleological process. This means that development of solutions is not affected by pre-determined concepts or designs; a theoretical model did not guide the search for a solution and thus did not delimit the solution space. Evolution essentially proceeds from trial and error, arbitrarily tinkering with the best current solution at hand. The human approach of using a guiding model allows for efficient solutions, yet often narrows down the set of possible solutions; any solution outside of the concepts – “outside the box” – is not regarded. Evolution is a method of problem solving which inherently remains “outside of the box”.

With this in mind, it is clear that the study of biomaterials, their formation processes, design motifs, and constituents is a fruitful and enlightening discipline. In this essay, we will carve out the limitations of current attempts at biomimetic mineralization and identify three main frontiers which currently challenge our adaption of the various and somewhat spectacular findings in the field of biomaterialization. We will show that our endeavor must tackle multiple dimensional frontiers in order to be prepared for a new level of biomimetic ceramic design, we must push the limits of temporal, spatial, and mechanistic control in biomimetic mineralization.

2. TOWARDS DYNAMIC CONTROL OF MINERALIZATION – THE STATIC, QUASI-STATIC, AND DYNAMIC GENESIS OF BIOMINERALS

The formation of bivalve and gastropod shells, of antlers, bones, teeth and egg shells all falls under the umbrella term “biomineralization” [6]. However, they differ tremendously, especially in regard to temporal control of the mineralization process, both during formation and/or after completion of the biomineral. Certain biominerals, such as tooth enamel and egg shell are initially deposited through active bio-mineralization. Upon completion, their fate is no longer under direct control of the organism or of the mineralizing cells. In such cases, full functionality is completed but not requested until afterwards. In a chronological sequence, function follows formation. Similar scenarios are common in biological systems, as exemplified by teeth, egg shells, coccoliths, and mollusk shells. Based on these observations, we can introduce a differentiation between *static* vs. *dynamic* biomineralization. In static mineralization processes, the functionality of the completed biomineral remains unaltered by the mineralizing organism. Thus, when analyzing material properties we can restrict our analysis to the final and static biomineral form. Biomineral alterations, *e.g.* by remodelling or certain types of extrinsic healing, would clearly indicate a dynamic biomineralization process.

Egg shells serve as a classic example of static biomineralization processes [7, 8]. Egg shells are designed to protect the interior but to break easily at the time of hatching. In the hen oviduct, about 20 g of calcium carbonate is laid down on a thin membrane which acts as a substrate. While wandering through the oviduct, the shell increases in thickness and is finally wrapped again in a thin organic sheet. Once the mineralization process is completed, the egg shell is ready to function and remains nearly unaltered, except certain leaching effects during incubation. Additional mineralization does not occur and would even be counterproductive as the shell needs to fracture easily from the inside-out to allow the fledgling to hatch. Other classic examples of static mineralization include the various kinds of known pathological mineralization and in general non-graded biominerals.

The capacity of the bone to remodel and heal exists in stark contrast to the concept of static biomineralization; bone is clearly a product of a highly dynamic biomineralization process. Bone tissue is hard and rigid. Bones are made from calcium phosphate in the form of a highly substituted hydroxyapatite, interwoven with organic collagen fibrils, and interfused with various types of proteins and polysaccharides along with smaller organic molecules such as citrates; its complex composite organization confers superb resistance to fracture. Bone simultaneously grows and functionally operates while its function and growth dynamically adopts to the needs of the host organism. For an organism in its

juvenile stages, it is inevitable that bone – serving as an endoskeleton – adapts and grows together with the increasing body volume. Since it would restrict and limit further growth, a static process is not possible. Static biomineralization is only feasible for exoskeletal systems, such as exhibited by shells (eggs, bivalves, or snails), or cuticles (*e.g.* crustaceans or coccoliths), where the need for expansion is met either by periodic and complete exoskeleton exchange, *i.e.* molting, or by extending an already existing exoskeleton (*e.g.* bivalves and snails). Only in specific cases (such as sponges) do we find that non-remodelled endoskeleton is used. Such organisms, though, are of low complexity compared to bone-reinforced organisms, and the body can adapt to a static endoskeleton while growing. In dynamic biomineralization, the endoskeleton adapts to the body's needs.

Remodelling and self-healing are well-known characteristics of bone that single it out from the majority of biominerals. Antler, which is comparable to bone with respect to its structure, composition, and mode of growth, does not experience remodelling or self-healing. And there is more to it: Julius Wolff revealed in 1892 that bone adapts to the external mechanical load it experiences [9]. Wolff's law describes the phenomenon which is used in both archeo-osteology and medicinal osteogenic loading which increases healing rates and bone density [10 - 12]. The concept of dynamic mineralization, which allows for alteration after completion, paves the way for self-adaptive materials, and leads to a new concept, that of potentially “smart” solid state materials.

Effective exploitation of this route is still barred since bone formation, remodelling, and self-healing are cell governed processes; in which (chiefly) three cell types, osteocytes, osteoclasts, and osteoblasts are involved.

Osteoblasts are bone-forming cells, osteoclasts are bone-destroying cells, involved in bone-resorption. Osteocytes are thought to be embedded cells, sensing mechanical pressure in the mineralised bone tissue. When triggered by an external stimulus (fracture or external load), they direct osteoclasts and osteoblasts to form and/or resorb, thus fomenting specific responses to external needs experienced by the organism. To mimic or design such a process *in vitro* is highly challenging since *in vivo* processes involving formation and remodelling in native bone are not yet fully understood.

Investigating differences between static and dynamic biomineralization in more detail, we note that mollusk exoskeleton, (bivalve, snail shell, and crustacean armature), is strong and resistant (in response to evolutionary pressure), protecting the animal from extrinsic threats such as predator attacks and rock displacements. Made of calcium carbonate with a small percentage of organic matrix, high

strength and toughness is achieved, up to 3000 times higher than in pure mineral [13]. In contrast to bone, mollusk exoskeleton is not interspersed with cells. In bivalves, the mineralization is accomplished by a layer of epithelial mantle cells attached to the inner side of the shell. The shells grow from the inside - outwards, the inner side represents the growth front. These cells release, probably *via* vesicular exocytosis, the components of the growing shell to an extracellular lumen – the extrapallial space – in which inorganic components feed mineral growth and the organic components guide polymorphism, crystallographic orientation, or crystal growth rates. The finalized shell is acellular, with no sensing organ that might react to stress or damage, and trigger remodelling. The growth of the shell occurs *via* continuous mineralization, a virtually continual layer-by-layer deposition of mineral. The outer edge, *i.e.* the lip, and also the inner shell surface are constantly mineralized. This understandably results in continuous growth in shell length and thickness, allowing the shell to grow with its host. However, this view is clearly oversimplified. Visual inspection of bivalve shell reveals differing layers combined into one shell, *e.g.* calcite prisms in the outer layer and an inner nacreous layer – forming a graded and layered material. This tells us that the mineralization process produces static biomineral; yet the biomineralization process itself changes with time, being clearly dynamic. Thus, we have a mixed-type of biomineralization, which one may call quasi-static biomineralization: the post-completed biomineral itself is unaltered, but characteristics of the mineralization machinery are controlled and change over time. We find similar quasi-static biomineralization in certain crustacean and sponge endoskeletons; most of these biomineralization processes are indeed quasi-static. Even kidney stones present layered structures; evidence of deposition cycles. Temporal control of a (bio-) mineralization process, whether by design or by accident allows formation of layered and structured materials, and represents a key step towards hierarchical and graded mineral-based materials.

What if the organism must fight against wear and degradation while relying on a static or quasi-static mineralization? Mammalian teeth may serve us here as a case study; their formation can be clearly classified as a quasi-static biomineralization process. Once amelogenesis is completed, the enamel-forming ameloblasts are lost and, as soon as exposed, the biomineral starts to perform its functions without further remodelling [14, 15]. Self-healing is not possible – as we all unfortunately know – since no sensor organs are embedded within the enamel which itself remains, out-of-body, and thus out of reach. In order to cope with such a situation and to ensure proper functionality of this essential biomineral, most mammals are diphyodont or even polyphyodont. Manatees, crocodiles, and sharks are well-known species which renew their teeth regularly. Only in a few mammals, especially rodents, enamel is continuously produced. However, this demands continuously growing teeth, and thus continuous wear has to be guaranteed [16].

The teeth of poly- and diphyodonts have to be classified as quasi-static biominerals; human teeth demonstrate this clearly: remodelling and self-healing are not possible. In former times, two sets of teeth apparently sufficed for a life time. Today, due to a remarkably increased life span in humans and a fundamentally modified nutrition base, our teeth require a lot more care. As a bottom line to these observations, we understand that the different dynamic types of biomineralization also relate strongly to their specific functions and the resulting energetic costs imposed on the biomineralizing organism. Bone experiences constant remodelling, which is strongly interrelated with bone vascularization and bone healing. Vascularization, as a matter of fact, weakens the mechanical properties, yet allows for self-healing and the genesis of light-weight material. In the case of teeth, the demand is high for hardness, *e.g.* in order to grind food. This excluded solutions such as vascularization (a premise for self-healing) since they would have weakened the mechanical performance of the bioceramic tool. The existence of diphyodont mammals shows clearly that tooth formation (and dentition, *i.e.* exchange) is a burden for the organism. So it seems that it was evolutionarily beneficial, to rely on only two dentition stages [14, 17].

Taken together, we see that biominerals must vary tremendously in terms of the temporal characteristics of their formation processes, and that these characteristics are adapted to the function of the biomineral. It is obvious that mimesis of a static or quasi-static mineralization process is much less complicated than the highly dynamic case of bone. Static processes can be mimicked using simple precipitation reactions, whereas quasi-static processes need a setup in which the composition of a precipitation system is altered in a controlled fashion during the course of the mineralization process. A fully dynamic mineralization process could be represented as a bio-inspired ceramic, able to actively remodel itself and (by this) allow for some strong and non-ebbing self-healing capacity. A successful adaption of this concept would be of huge impact in various materials design fields. A self-remodelling concrete or self-paving street is just a first glimpse into potential applications. Quasi-static processes, in which some ongoing mineralization is tuned and precisely controlled for formation of structure, may emerge as a flourishing field of research, allowing for the generation of hierarchical structures, similar to certain biological counterparts. Such approaches, by switching from a static view of ceramics to bio-inspired and quasi-dynamic concepts, are fundamentally changing the field of solid-state materials (Fig. 1).

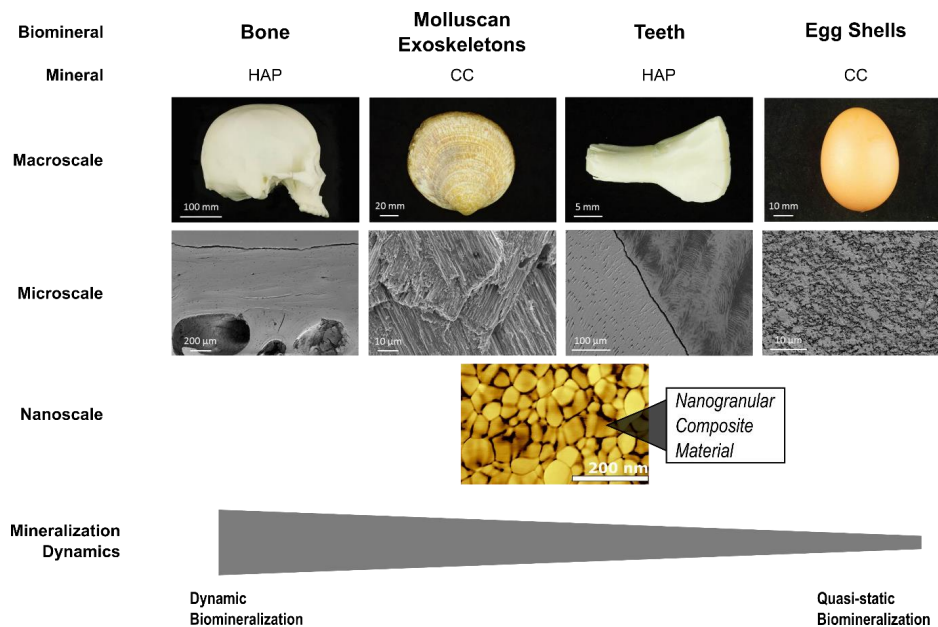


Fig. (1). Overview of different biomineralization processes, their constituents, their macro- to nano-structures along with a tentative classification of their mineralization dynamics. From left to right: Bone (hydroxyapatite), mollusc exoskeleton (calcium carbonate, crossed-lamellar structure of the bivalve *Glycymeris glycymeris*), teeth (hydroxyapatite), and egg shells (calcium carbonate, from *Gallus gallus*). The structures have relatively uniform appearance on the nanoscale, a nanogranular composite structure – depicted here using an example from a calcareous bivalve nanostructure. Atomic force microscopy reveals a fine grained structure and suggests a soft and thus organic matrix located at the grain boundaries.

3. HIERARCHICAL MINERALIZATION – CONTROL OF HIERARCHY AND STRUCTURES ACROSS MULTIPLE LENGTH SCALES

The task-optimized properties of biominerals are induced by a complex hierarchical structure design across many length scales, from the nano- to the macroscale [18 - 21]. Function emerges from the structure of the biomineral, not from inherent properties of the pure organic or inorganic components alone. This allows usage of ubiquitous and mundane substances like calcium carbonate. Nature thus imprints function on non-functional material, instead of using expensive or barely-available rare raw materials, in order to achieve a high level of performance, Nature has mastered the art of hierarchically designing a material for a given task.

Virtually all biominerals feature a hierarchical design, in which every level of hierarchy affects the macroscale properties of the final biomineral. Nacre, one of the most intensively studied biominerals, is praised for its excellent mechanical properties and often serves as an ambassador for biominerals – it may also serve

excellently as a show-case of hierarchical organization [22 - 25]. Generations of researchers have devoted much work to elucidate the origin of nacre's remarkable properties, its formation processes, and its direct or indirect mimesis. These studies reveal the hierarchical nature of nacre. In a nutshell, the mechanical properties are rooted in three aspects: an increase in crack length, a relatively controlled crack path, and an increasing work of fracture advancement along this controlled crack path [23, 26 - 29]. The overall concept is a layered structure, with an intertabular organic matrix. The cracks are typically guided along an intertabular pathway, along which the intertabular organic matrix increases energy dissipation and allows for self-healing, (and thus its quasi-plastic behaviour) [30, 31]. Additional effects like dovetails, undulating aragonite tablets, or tablet bridges provoke interlocking during tablet sliding [26]. If the acting forces are too high, causing fracture of the mineral tablets, we find a similar behaviour, again within the tablets: the tablets are not made of pure aragonite but represent an organic-inorganic composite material with a fine granular structure [23, 32]. Several studies have proposed, and it has been corroborated that these granules are coated with an organic and quasi-intracrystalline matrix which is able to affect crack propagation in a fashion similar to the intertabular organic matrix [30, 32].

If we consult other bivalve microstructures beside nacre, we find a remarkable diversity of complex structures [33]. However, if we take a close look at the characteristics of the non-nacreous bivalve structures, we find a repeating concept: a maximization of the grain boundary interface at which an organic matrix is located. This design concept is also true for non-calcareous structures, and can be spotted also in bone, crustaceans, and glass sponges. Thus we note that all of these mesostructures maximize their composite nature; and in case of intergranular fracture, maximize the impact of the few percent of organics on the fracture mechanics.

Following thorough analysis of biominerals, it becomes clear that virtually all biominerals share a universal nanoscale structural motif which is independent of both the chemical composition and the meso-to-macrostructure of the host biomineral. All feature a nanogranular composite structure similar to the one discussed for nacre. A plurality of biominerals are based on this structure, for example mollusks, glass sponges, and apatitic human bone. The size of the granules may vary; however, the average granule size is typically 100 nm [32].

Let us now, for an instant, switch gears and examine a case in which nacre was successfully mimicked. In the work of Bouville *et al.* a ceramic material with five hierarchical levels was produced [34]. It presented crack deflection, load redistribution, and delamination in a fashion similar to nacre. The structure was generated in a three-step process. First, an aqueous colloidal suspension of all the

required building blocks and processing additives was prepared. The elements were then co-aligned using ice templating, a procedure in which the suspended particles are expelled from the moving solidification front. A pressure-assisted sintering step at 1,500°C concluded the processing of a nacre-like alumina. The material then showed a hierarchical organization across numerous length scales. Crystals were ordered into long and medium range and cling together by a secondary phase with a lower stiffness; the ceramic platelets, of similar size to nacre, are narrowly packed. Ceramic bonds between the individual platelets and nano-asperities on the surface of the ceramic platelets allowed for interlocking.

Taking this clearly successful mimesis as a case example, it became clear that we currently use multiple steps of processing to achieve hierarchical organizations in materials and therefore apply a top-down approach for material structuration. A light scan of the current literature reveals that man-made hierarchical materials often rely on such top-down approaches, only rarely is a bottom-up approach used in which the system is empowered to self-organize by the physicochemical behaviour of its constituents. However, the concept of self-organization is inherent to our native counterpart; and in general to biomineralization *in vivo*—especially in quasi-static processes. Top-down processing of biomimetic materials may well represent a successful pathway to static biomimetic mineralization, however, it is insufficient and inefficient to produce quasi-static or dynamic biomimetic mineralization. Recall, that in case of quasi-static biomineralization processes we can stop the process at almost any time, except the earliest biomineral stages, and we nevertheless receive a functional material. Take a mollusk shell – the increments in growth are virtually infinitesimal but nevertheless the shell is functional at any time of growth, except in its very early, *i.e.* larval, stages.

For biominerals, it is still an enigma as to which self-organization processes generate mesostructures. Bouligand structures in bone or chitin-based exoskeletons have been reported as templated by liquid crystal [35], an idea which was also proposed for nacre [36]. With these examples of quasi-static mineralization, Nature teaches us to use self-assembling three-dimensional scaffolds, (*i.e.* bottom-up approaches), instead of imprinting structure after the formation of our material, (*i.e.* by a top-down approach). Let us now combine the concept of bottom-up structuration (*i.e.* a self-organizing template during crystallization) with a quasi-static mineralization process (*i.e.* a process in which we can alter our reaction conditions during mineral production). From this combination, we can superimpose another layer of complexity onto our growing structure. Quasi-static mineralization essentially allows us to produce layered and graded structures with relative ease – a motif which is often observed in biominerals.

By controlling all of these crystallization variables, nature is able to build highly complex and highly hierarchical structures while achieving temporal and spatial control. As of yet, we are not able to reproduce similar control over reaction conditions (*i.e.* quasi-static mineralization) together with simultaneous structure generation using a bottom-up approach. This clearly represents another frontier in bio-inspired mineralization. Mastering this challenge will have a huge impact on the field of bio-inspired ceramic materials.

4. NONCLASSICAL MINERALIZATION – COLLOID-MEDIATED MINERALIZATION PROCESSES AS A SOURCE OF FUNCTIONAL NANO- TO MESO-STRUCTURES

Understanding and replicating the complex and curved morphologies of biogenic solid-state materials is challenging, and the degree to which nature can control crystallization is especially striking. Morphological control on all length scales, functionality during growth, and self-healing in biominerals indicate a more complex crystallization mechanism than that described by classical crystallization theory. Certain crystallization reactions do not fit into classical crystallization theory and point to the existence of a pathway well outside the classical picture of ion-mediated growth [37, 38].

In classical crystallization theory, a critical nucleus is spontaneously formed by phase transition in a supersaturated solution of ions or molecules. Single ions or molecules attach to the nucleus as long as the solution is supersaturated, and a thermodynamic equilibrium is soon reached. Further crystal growth is only possible by Ostwald ripening, dissolution of small crystals, and growth of larger ones. Due to the need for surface energy minimization, crystals grown by classical processes exhibit a faceted shape. However, biominerals typically deviate distinctly from the familiar faceted crystal shapes with sharp edges and flat surfaces. This already points to certain deficiencies in the classical crystal growth model, especially regarding the complicated scenario of biomineralization.

Nature creates such morphologies not by employing a direct pathway to a crystalline material, but by taking a detour *via* transient amorphous intermediates, a pathway “less travelled”. This amorphous, and thus isotropic material, is easily used during shaping of the biomineral. In a second step, it transforms into a crystalline material by a solid-to-solid transformation which allows it to retain the non-equilibrium shaped morphology in the final crystalline state. Employing this so-called pseudomorphic transformation (similar to glass ceramics) in biomineral formation provides an enormous amount of control over the shape of the new phase [39]. Currently, various studies have adopted this route (*via* an amorphous precursor) and are enjoying remarkable success in generating non-equilibrium

morphologies. This represents a first step towards true mastery of many crystallization pathways that remain outside the classical model framework.

Besides an initial lead for nonclassical crystallization pathways in biomineralization, further *in vitro* and *in vivo* observations point towards nonclassical crystallization mechanisms. Earlier in this essay, we introduced a uniform nanoscaled granular structure which seems to unite biominerals. This fine nanogranular structure has stirred multiple debates concerning its origin. In the case of many biominerals, *e.g.* sea urchin spines [40], pearl oyster nacre [25], red coral [20], and eggshells [41], it was speculated that the grain structure was caused by attachment of nanoparticles during growth. Since these biominerals behave like a single crystal on the macroscale but feature nanoscale structuration, they were defined as mesocrystals, a term introduced by Cölfen and co-workers [42]. Based on the fact that the first synthetic mesocrystals were formed *via* oriented-attachment, a process in which already crystalline nanoparticles self-assemble in a near-perfect crystallographic register, this first explanation for mesocrystallinity in biominerals supposed an oriented attachment process. However, as we have already seen, biominerals form *via* an amorphous phase which has been shown to crystallize *after* assembly. This essentially means that biominerals use a different nonclassical process – a process one may call colloid attachment and transformation (CAT). Amorphous colloids attach – be they liquid droplets or already solid amorphous particles – and the formed nanogranular bulk material transforms after self-assembly. Multiple studies have demonstrated an amorphous growth front in biominerals, which might evidence a particle-attachment process driving nacre growth. In this study, we analyzed early nacre formation and identified that fibrous nacre essentially consists of individual nanoparticles which assemble, and as soon as a certain particle-number-density is reached, merge and coalesce towards a space-filling nacre platelet. Based on all of these findings, we recently developed a model for *in vivo* nonclassical mineral growth which allows generation of nanogranular fine structure in biominerals [32]. A stabilized amorphous precursor is formed in lithosomes, and in a second step these vesicles are exocytosed. The amorphous nanogranule then attaches to the growing biomineral. In an alternative pathway, re-dissolution of the amorphous deposit in the cell may occur, and the resulting ions are released to the extracellular space together with biomacromolecules, thus forming amorphous mineral precursors extracellularly. Phase transformation of the amorphous nanogranular biomineral is triggered by dehydration. The highly hydrated amorphous phase gradually loses water and primary nucleation is induced heteroepitaxially by specific proteinaceous nucleators. Further, granules in contact with a crystalline nanogranule transform by homoepitaxial nucleation.

These various lines of evidence for *in vivo* particle-mediated mineralization are

paralleled by *in vitro* studies which also point to nonclassical models of crystal formation. Gower *et al.* [43] described the so called polymer-induced liquid-precursor (PILP) process as a possible biomineralization process which leads to nonequilibrium crystal morphologies [43]. Polyelectrolyte additives, *e.g.* poly-acrylic acid and poly-aspartic acid, mimic the function of biopolymers in biominerals, and guide the process through a nonclassical pathway: small droplets form by liquid-liquid phase separation, having sizes of up to 2-4 μm . These droplets aggregate and form a precursor film which dehydrates; finally causing a pseudomorphic amorphous to crystalline phase transformation [43]. Magnesium [42] or proteins such as caspartin or ovalbumin [32] can also act as inhibitors of the classical crystallization mechanism; by inducing or permitting the PILP process. A recent *in-situ* AFM study evidenced the existence of gel-like precursors for the crystallization mechanism of calcium carbonate on a calcite surface [32]. Wolf *et al.* [32] and Homeijer *et al.* [44] observed an amorphous liquid-like phase for differing metal carbonates. On the other hand, processes of oriented attachment were observed for titania nanocrystals under hydrothermal conditions, and for many other materials systems such as iron oxide. Spontaneous self-assembly of neighboring nanocrystals results in a common crystallographic orientation and attachment of crystals to the lattice-matched face, leading (for instance) to chain-like anatase nanostructures formed *via* oriented attachment [45].

All of these investigations give a first impression that numerous crystal formation pathways exist, and that they occur outside of classical text-book knowledge. The endeavours of biomimetic mineralization, and the study of biomineral formation have revealed severe deficiencies in our (academic) knowledge of crystallization and have also widened our view. Nonclassical pathways seem to be essential for biomineralization processes, the mechanisms and their full complexity have yet to be fully explored. Many details concerning these mechanisms remain unclear and must be elucidated. This lack of mechanistic insight represents, from our point of view, the third largest obstacle (which must be removed) in the field of bio-inspired mineralization. Nonclassical processes seem to be ubiquitous; however, the fundamental laws involved in these specific processes of self-organization are still enigmatic. Without mastery of the various steps involved in nonclassical crystallization, we remain restricted in our knowledge to the well-understood pathways of classical crystallization. This clearly represents a limitation of our biomimetic toolbox: by shifting the crystallization process from classical to nonclassical, nature enjoys a significant influence on the crystallization process itself. Not only having direct access to a nanogranular composite structure, Nature also controls the final polymorph, and (by controlling which additives are incorporated and the amount of their incorporation) the time-frame in which the crystallization takes place [46]. By travelling along the crystal formation pathway

via amorphous precursors, not only non-faceted, non-equilibrium morphologies are feasible but also distinct doping of the final material is possible, which is the case for magnesium-rich calcites in sea urchin teeth [47], for manganese incorporated in bivalve shells [48], and for bone in general [49, 50]. Nonclassical crystallization provides access to nanoceramic composite materials, a class of materials whose full potential has not yet been tapped.

CONCLUSION

While revisiting pertinent model organisms and biomineralization and to facilitate progress, this essay assessed which frontiers are yet to be dominated in biomimetic mineralization. We identified the three principal challenges arising in the endeavour to mimic the yet unparalleled craftsmanship of Nature in solid-state chemistry and material design:

- i. *Temporal control in biomineral formation.* Biominerals, such as bone or mollusk exoskeleton are often subject to delicate temporal controls, be it during growth or throughout their life-time. We identified different classes of temporal control, ranging from static to dynamic biominerals. For static biominerals, functionality succeeds completion of biomineral growth; most biominerals belong to this class. To be precise, most of these static biominerals experience temporal control in their formation which allows continuous growth and a layered, functional structure. We denominate these biominerals as quasi-static. Some biominerals can be classified as fully dynamic bioceramics – experiencing constant remodelling, growth, and self-healing, yet without affecting the overall functionality of the biogenic ceramic. They serve and are functional from very early stages. They are not built to function, but rather they grow while functioning – a feature which bears remarkable potential for biomimetic mineralization. However this feature is likely the most difficult to achieve;
- ii. *Formation of hierarchically structured materials, with functional structures across length scales.* In biominerals, Nature creates various interwoven structures over a wide range of length scales, from the nano- to the macro-scale. Control-loops and self-organization processes seem to guide the emergence of such structures. Understanding these control-loops and transferring them to a new generation of materials would allow creation of smart materials that react to changing environments, yielding differing responses in function of the length-scale at which a response has been triggered; and
- iii. *Mechanisms (enigmatic) of nonclassical crystallization processes that drive biomineralization.* Recently, it was realized that a range of biominerals seem to grow *via* colloid-driven accretion processes, and not through classical ion-

by-ion growth. Such enigmatic processes allow morphological control at all length scales, functionality during growth, and self-healing. Organic and inorganic matrix components guide mechanisms towards non-classical crystallization, and may even trigger different pathways: oriented attachments, colloid-attachments and transformation processes, or even the emergence of liquid-condensed mineral precursor phases.

In the future, to unlock the full potential of bio-inspired ceramic design, biomimetic mineralization must focus on addressing these frontiers. Each frontier involves exceptional potential for imprinting structure or functionality onto solid-state materials. This, in turn, may enable us to confer functionality to benign and mundane materials – a capability which, so far, only belongs to Nature.

CONSENT FOR PUBLICATION

Not applicable.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Sustainable and Safe Construction Biomaterials: Biocements and Biogrouts

Volodymyr Ivanov* and Viktor Stabnikov

National University of Food Technologies, Kyiv, Ukraine

Abstract: Biocement is a mixture of at least three components: (i) a principal inorganic component producing binding matter, (ii) a component that changes pH and initiates precipitation of binder; and (iii) an enzyme, live microbial cells, or dead but enzymatically active microbial biomass that catalyzes pH changes and/or other biochemical reactions. The inorganic component is usually a dissolved calcium, magnesium, or iron salt which is transformed into a non-dissolved compound. A component that changes pH and supplies CO₂ for carbonation is usually urea, nitrate, formate or acetate, that are hydrolyzed, oxidized or reduced under catalytic action of microbial cells or enzyme. Biogrouts are similar to biocements, but used in lower dosages than biocements. Their application objective is to diminish hydraulic conductivity of soil, fractured rocks, or concrete cracks. A principal advantage of biocements and biogrouts over conventional cements and grouts is the low viscosity of their solutions/suspensions; such that biocements and biogrouts can be used for deep penetration into porous soil, fractured rocks, or concrete cracks. There are about 15 different types of biocement/biogrout. The most popular class of biocement and biogrout is abbreviated as MICP (Microbial Induced Calcite Precipitation), and based on the formation and adhesion of calcium carbonate crystals produced from a concentrated solution of calcium ions and urea. The process is used to fill pores and bind particles with calcium carbonate crystals. This is initiated by urea hydrolysis by urease-producing microorganisms but it is not environmentally-friendly process. Specific killing of bacterial cells that leave their urease activity intact increases the biosafety of biocementation/bioclogging processes. Biogrout with killed bacterial cells has been demonstrated to decrease hydraulic conductivity of sand from 5×10^{-4} m/s to 3×10^{-8} m/s. To decrease the expense of biocement/biogrout, a bioagent can be produced from hydrolyzed activated sludge. In practice, biocements and biogrouts can be used for strengthening and sealing slopes, agricultural channels, the construction sites, the aquaculture and wastewater treatment ponds, the landfill and soil-polluted sites, the dams and retaining walls, the tunneling space before or after excavation, for the road construction, dust and erosion control, for decontamination of CBRN agents on polluted land and infrastructure, for the coating of the artificial coral reefs or concrete coastal constructions, and many other environmental, agricultural and civil engineering applications.

* **Corresponding author Volodymyr Ivanov:** National University of Food Technologies, Kyiv, Ukraine; Tel: +380664030226; E-mails: cvivanov111@gmail.com, cvivanov@nuft.edu.ua

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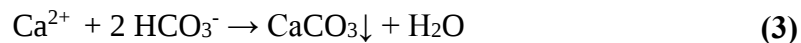
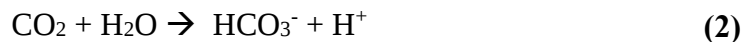
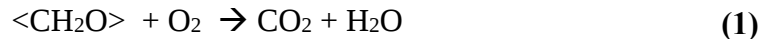
1. INTRODUCTION

Biocement is a mixture of at least three components: (i) an inorganic (principal) component producing binding matter, (ii) a component that changes pH and produces carbonate, phosphate, sulfide, or hydroxyl groups for binder precipitation; and (iii) an enzyme or microbial biomass which catalyzes pH changes and the release of carbonates or phosphates. The principal inorganic component is usually a dissolved calcium, magnesium, or iron salt, which is transformed into a non-dissolved compound that binds the particles. The component that modifies the pH and supplies CO₂ for carbonation is usually urea, nitrate, formate or acetate, which, when under the catalytic action of microbial cells or enzymes, can be hydrolyzed, oxidized or reduced. Biogrouts are similar but, are used at lower dosages than biocements. Biocements and biogrouts are used to diminish the hydraulic conductivity of soil, fractured rocks, or concrete cracks in construction, agriculture, aquaculture, or environmental engineering.

2. BIOCEMENT/BIOGROUT FOR CRYSTALLIZATION OF CALCIUM CARBONATE BY HYDROLYSIS OF UREA AT MOLAR RATIO CA: UREA = 0.5 – 2.0 (CAUR BIOCEMENT/BIOGROUT)

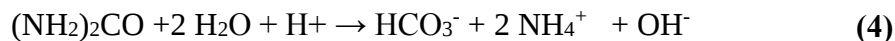
In nature, calcium carbonate is produced by chemotrophic and phototrophic microorganisms that produce hydrogen carbonate ions while simultaneously increasing the pH of microenvironment [1 - 3].

Chemotrophic precipitation of CaCO₃:



where: $\langle \text{CH}_2\text{O} \rangle$ is the empirical formula for carbohydrate.

However, there must be an additional reaction to neutralize protons, for example, urea hydrolysis by the enzyme urease:



This reaction is also a source of bicarbonate, so precipitation of calcium carbonate will (in this case) occur without oxidation/reduction, *i.e.* it can be performed by either aerobic or anaerobic urease-producing microorganisms, or using the enzyme urease:



Urea is released to the environment as a final product of nitrogen metabolism in mammals, therefore many soil microorganisms produce the enzyme urease.

There may be also phototrophic CaCO_3 precipitation:



Examples of such activity in nature are stromatolites and coral reefs [4].

Biocementation, as presented in Equations 1-5, is currently the most popular method used for aggregation, clogging, and strengthening of soils [5 - 15], or for immobilization of soil pollutants [9, 16, 17]. It is often called Microbial-Induced Calcium Carbonate Precipitation (MICCP) or Microbial-Induced Calcite Precipitation (MICP). Actually, neither term is scientifically correct since calcite and precipitation are not exclusive features of the process. There are many other chemotrophic and phototrophic types of MICCP. A more accurate though less convenient term would be “urease-dependent calcium carbonate crystallization on solid surface”. More convenient terms for differing biocements are presented in Table 1. CaUr biocements and others are described below.

3. THE DIVERSITY OF BIOCEMENTS AND BIOGROUTS

A diversity of practically applicable biocements/biogROUTS is presented in Table 1.

Table 1. Biocementation processes and related biocements/biogROUTS.

Biocementation Process: Principal Chemical Equation	Most Often Used Term for the Process	Proposed Abbreviation: Biocementation Process and Biocement
Crystallization of calcium carbonate due to hydrolysis of urea at molar Ca ratio: urea = 0.5 – 2.0: $\text{Ca}^{2+} + (\text{NH}_2)_2\text{CO} + 2 \text{H}_2\text{O} \rightarrow \text{CaCO}_3\downarrow + 2 \text{NH}_4^+$	MICCP / MICP	CaUr

(Table 1) cont.....

Biocementation Process: Principal Chemical Equation	Most Often Used Term for the Process	Proposed Abbreviation: Biocementation Process and Biocement
Crystallization of calcium carbonate due to aerobic bio-oxidation of calcium formate or calcium acetate $(\text{CH}_3\text{COO})_2\text{Ca} + 4 \text{O}_2 \rightarrow \text{CaCO}_3\downarrow + 3 \text{CO}_2\uparrow + 3 \text{H}_2\text{O}$	Absent	CaOx
Crystallization of calcium carbonate due to decay of calcium bicarbonate and drying: $\text{Ca}(\text{HCO}_3)_2 \rightarrow \text{CaCO}_3\downarrow + \text{CO}_2\uparrow + \text{H}_2\text{O}$	Absent	CaBic
Crystallization of calcium carbonate due to decay of calcium bicarbonate under action of urease on urea: $\text{Ca}(\text{HCO}_3)_2 + \text{OH}^- \rightarrow \text{CaCO}_3\downarrow + \text{HCO}_3^- + \text{H}_2\text{O}$	Absent	CaBicUr
Crystallization of calcium carbonate due to delayed decay of chelated calcium bicarbonate and action of urease on urea: $\text{EDTA-Ca}(\text{HCO}_3)_2 + \text{OH}^- \rightarrow \text{CaCO}_3\downarrow + \text{HCO}_3^- + \text{H}_2\text{O} + \text{EDTA}$	Absent	CaBicChel
Biocementation based on production of carbonates by denitrifying anaerobic heterotrophic bacteria $(\text{CH}_3\text{COO})_2\text{Ca} + 8/5 \text{NO}_3^- \rightarrow \text{CaCO}_3\downarrow + 4/5 \text{N}_2\uparrow + 3 \text{CO}_2\uparrow + 3 \text{H}_2\text{O} + 8/5 \text{OH}^-$ or $12 \text{NO}_3^- + 5 \text{C}_2\text{H}_5\text{OH} + 6 \text{Ca}^{2+} \rightarrow 6 \text{CaCO}_3\downarrow + 6 \text{N}_2\uparrow + 4 \text{CO}_2\uparrow + 15 \text{H}_2\text{O}$	Absent	CaDen
Biocementation based on production of sulfides from gypsum by sulfate-reducing anaerobic heterotrophic bacteria: $\text{CaSO}_4 + \text{CH}_3\text{COOH} \rightarrow \text{CaS}\downarrow + 2\text{CO}_2 + 2\text{H}_2\text{O}$	Absent	CaSul
Biocementation based on production of carbonates on soil surface by phototrophic bacteria: $\text{Ca}^{2+} + \text{light} + \text{HCO}_3^- + \text{OH}^- \rightarrow \text{CaCO}_3\downarrow + \text{H}_2\text{O}$	Absent	CaPhoto
Crystallization of calcium phosphate (hydroxyapatite) due to hydrolysis of organic phosphates and enzymatic production of hydroxide ions: $10 \text{Ca}^{2+} + 6 \text{R-PO}_4 + 6 \text{H}_2\text{O} + 20 \text{OH}^- \rightarrow \text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2\downarrow + 6 \text{R-OH} + 12 \text{H}_2\text{O}$	Absent	CaPhosOrg
Crystallization of calcium phosphate (hydroxyapatite) due to increased pH from urease activity: $10 \text{Ca}^{2+} + 6 \text{H}_2\text{PO}_4^- + 14 \text{OH}^- \rightarrow \text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2\downarrow + 12 \text{H}_2\text{O}$	Absent	CaPhosUr
Crystallization of calcium and magnesium carbonates due to hydrolysis of urea at molar ratio (Ca +Mg): urea = 0.5 – 2.0: $\text{Ca}^{2+} + \text{Mg}^{2+} + \text{CO}(\text{NH}_2)_2 + \text{UPB} \rightarrow \text{CaMg}(\text{CO}_3)_2\downarrow + 2 \text{NH}_4^+$	Absent	CaMgUr

(Table 1) cont....

Biocementation Process: Principal Chemical Equation	Most Often Used Term for the Process	Proposed Abbreviation: Biocementation Process and Biocement
The combined calcite and struvite (NH_4MgPO_4) precipitation using triple superphosphate and magnesium salt to avoid the production of free ammonium and release of ammonia to atmosphere during biocementation: $\text{Ca}(\text{H}_2\text{PO}_4)_2 + 2 \text{Mg}^{2+} + \text{CO}(\text{NH}_2)_2 + \text{H}_2\text{O} + \text{acid urease} \rightarrow 2 \text{NH}_4\text{MgPO}_4\downarrow + \text{CaCO}_3\downarrow$	Absent	CaMgPhos
Crystallization of calcium and magnesium carbonates due to aerobic bio-oxidation of calcium and magnesium formate or acetate: $(\text{CH}_3\text{COO})_2\text{Ca} + (\text{CH}_3\text{COO})_2\text{Mg} + 8 \text{O}_2 \rightarrow \text{CaCO}_3\downarrow + \text{MgCO}_3\downarrow + 6 \text{CO}_2\uparrow + 6 \text{H}_2\text{O}$	Absent	CaMgOx
Precipitation of ferric/ferrous hydroxide and carbonate from ferrous salt or chelate due to hydrolysis of urea [18]: $\text{Fe}^{2+} + 2\text{OH}^- \rightarrow \text{Fe}(\text{OH})_2$ $\text{Fe}^{3+} + 3\text{OH}^- \rightarrow \text{Fe}(\text{OH})_3$	Absent	FeHyd
Precipitation of ferric/ferrous hydroxide/ carbonate from ferrous salt or chelate due to aerobic oxidation of organic ferrous salt/chelate: $(\text{CH}_3\text{COO})_2\text{Fe} + 4 \text{O}_2 \rightarrow \text{FeCO}_3\downarrow + 3 \text{CO}_2\uparrow + 3 \text{H}_2\text{O}$	“Bioclogging by iron-oxidizing bacteria”	FeOx

Depending on the expense and availability of raw materials, different types of biocements and biogrouts can be manufactured. Limestone, dolomite, cement powder, and iron ore powder are the most often used raw materials for principal component production in biocements and biogrouts. These must be dissolved using hydrochloric, acetic, or formic acid. Liquid calcium chloride brine, is available for use as a road de-icing agent. The second component of biocements and biogrouts can be urea or superphosphate, which are common fertilizers. The third component is usually a bacterial biomass with specific enzymatic activity. Application of pure enzymes has been explored in several papers [19, 20], but it is too expensive for large-scale geotechnical applications. Bacterial cells with mineralizing enzymatic activity adhere to a surface and become the center of crystallization that ensures surface adhesion of the crystals produced. However, the use and application of live microorganisms in engineering is always a problem of because of biosafety and ecological concerns. Thus, the method described below can be used for the production of biosafe biocements/biogrouts.

4. MICROORGANISMS FOR BIOCEMENT/BIOGROUT

The microorganisms used as a source of urease activity for popular MICCP/MICP/CaUr biocements are alkaliphilic (growing at pH above 8.5), halotolerant (growing at concentrations of calcium and urea above 1M), Gram-positive bacterial species of the genera *Bacillus* and *Sporosarcina*. The strain *Sporosarcina pasteurii* ATCC11859 (DSMZ33, LMG 7130) is the most popular [5, 21 - 23]. Other physiologically similar species used for biocementation are *Bacillus megaterium* [24, 25], *B. sphaericus* [26, 27], *B. pseudofirmus* [28], *B. subtilis* [29], *Bacillus pumilus* [30], *B. lentus* [31], and some unidentified species [8, 10, 21, 26, 32] as well.

Certain halotolerant species of the genus *Staphylococcus* also exhibit high urease activity [33]. A halotolerant urease-producing strain of the Gram-positive bacteria *Staphylococcus succinus* was isolated from water of the Dead Sea (with 34% salinity) [10], however, strains of *S. succinus* are often hemolytic and toxigenic [34, 35], and the isolated strain was not used for biocementation studies and applications.

Urease-Producing Bacteria (UPB) for biocement/biogrout must: (i) be non-pathogenic; (ii) be the cells with low aggregation ability for deeper penetration into porous soil or fractured rocks; (iii) be able to adhere to the treated surface; and (iv) produce the enzyme urease active at pH 8.5 - 9.2 in a medium with a high salt concentration [36]. UPB are present in almost all terrestrial and aquatic sites where urea is a final product of nitrogen metabolism in mammals.

Differing types of biocement (other than MICCP) usually require specific microorganisms to activate the process, these include: nitrate-, iron-, and sulphate-reducing bacteria, acetate or formate-oxidizing bacteria, acidotolerant UPB, iron-oxidizing bacteria, and phototrophic cyanobacteria [36].

5. BIOCEMENTATION BIOSAFETY: USE OF ENRICHMENT OR PURE CULTURE

A UPB enrichment culture can be obtained by enrichment of soil samples with urea [10, 37]. It is relatively easy to select a UPB halophilic and alkaliphilic enrichment culture and many researchers use enrichment cultures based on halophilic and alkaliphilic bacteria for biocementation/biogrouting, or at times even consider indigenous microorganisms with *in situ* urease activity.

Enrichment cultures with urease activity have been selected from soil samples or *in situ* indigenous soil culture of microorganisms and proposed for calcium

carbonate precipitation in soils [7, 26, 38]. In comparison with pure strain of UPB, application of enriched microbial cultures allows less expensive urease active bioagent production.

Selection of UPB is performed in media with high salt concentration and at high pH [10]. This brings the opportunity to obtain liquid cultures with high urease activity, even under non-aseptic conditions [39].

It is well-known that many urease-active bacteria are opportunistic pathogens and include even such pathogens as *Helicobacter pylori*, which can infect the human stomach [10]. There are many known pathogenic species, which are also halotolerant and alkaliphilic. Even the above mentioned halophilic strain of *Staphylococcus succinus*, isolated from water of the Dead Sea with salinity of 34%, possesses urease activity [10]. The strains of *Staphylococcus succinus* may be hemolytic and toxigenic [35], and associated with infectious disease [34]. Stimulation of growth of indigenous urease-producing soil bacteria remains unsafe process because neither high pH nor salinity does not prevent the growth of urealytic and non-urealytic pathogenic bacteria.

Our long-term use under selective conditions of a UPB enrichment culture for alkaliphilic and halotolerant bacteria revealed that there were at least four strains VS8, VS1, VS21, and VS17, respectively making up 55%, 30%, 10%, and 5% of the total number of the colonies. The major representative was the *Yaniella* sp. / *Enteractinococcus* sp. strain VS8 with cells looking like micrococci. The dominating strain VS8 was from the family *Micrococcaceae*. It is important for the industrial process that bacteria of the genus *Yaniella* belong to Risk Group 1 and there were no references in the PubMed database (25 million citations for biomedical literature) on the potential pathogenicity of species from the genus *Yaniella*. The 2nd strain was the *Bacillus* sp. strain VS1 isolated by Stabnikov *et al.* [8] and used previously in our laboratory studies for bioclogging and biocementation. The 3rd urease-positive strain VS17 was a representative of the genus *Staphylococcus*. The 3rd urease-positive strain VS17 was close to *Staphylococcus* sp. R-25657 (identity 100%), and *Staphylococcus* sp. ZWS13 (identity 99%), *Staphylococcus* sp. JY04 (identity 99%), and *Staphylococcus cohnii* subsp. *urealyticus* strain CK27 (identity 99%). *Staphylococci* are always living on human skin, but some strains of *Staphylococcus* are pathogens causing different infectious diseases in humans and other mammals. *Staphylococcus cohnii* subsp. *urealyticus* strain CK27 (ATCC 49330), which is a close relative to the strain VS17, was isolated from human skin, and has a biosafety level 2.

The 4th strain VS21 was close to *Bacillus thuringiensis* serovar *kurstaki* strain HD1 (identity 99%); *Bacillus thuringiensis* serovar *galleriae* strain HD-29

(identity 99%); *Bacillus cereus* 03BB102 (identity 99%), and *Bacillus anthracis* strain IHB B 15126 (identity 99%). The strain *Bacillus thuringiensis* serovar *kurstaki* HD1 is an entomopathogenic strain, which is an environmentally compatible bio-pesticide used worldwide. *Bacillus thuringiensis* serovar *galleriae* strain HD-29 is also a strain of commercial bio-pesticide. The *Bacillus cereus* species includes opportunistic human pathogens; the *B. cereus* strain 03BB102, which is close to the strain VS21 was isolated from the blood of a patient who died as a result of severe pneumonia, probably caused by this bacterium. At the same time, some species can induce calcium carbonate precipitation. Species of *Bacillus anthracis* include mammal pathogens that cause the infectious disease anthrax, considered as biological warfare.

The experimental data showed that an enriched UPB culture may contain bacteria that are opportunistic or even real pathogens. In practice, only pure and biologically safe bacterial cultures should be used in bioclogging and biocementation.

6. PRODUCTION OF BIOSAFE BIOCEMENTS

A major point for the use of pure bacterial culture for MICP is biosafety related to all stages of biocement production and use: (i) biomass production, (ii) production and storage of biocement, (iii) injection into or spraying onto soil, (iv) persistence of introduced microorganisms in soil, (v) effect of introducing microorganisms on humans and environment. Due to the strong requirements for biosafety, it might be more practical to use not live but dead urease-active cells that are unable infect humans, plants, and animals.

The best way to ensure biosafety in environmental microbial introductions is to use crude urease killing the live bacterial cells, yet such that their urease activity remains. Applications of the pure enzyme urease for large-scale bioclogging of sand or other porous materials are technologically possible, but the enzyme may in fact be too expensive. Yet since bacterial cells with urease activity attach to the surface of material and form crystallization centers for the formation of calcium carbonate minerals, we therefore tested different methods to kill bacterial cells yet leaving their urease activity needed for biocementation/bioclogging.

Microbiological study of UPB enrichment cultures showed that the best approach is as follows: (i) use a pure culture of *Yaniella sp.* VS8 for bioclogging of sand; cells of *Yaniella sp.* VS8 are about half of the size of *Bacillus sp.* VS1 cells, and do not form large cell aggregates in calcium chloride solution, thus they may penetrate deeper into fine sand and fractured rocks; (ii) find a method to kill *Yaniella sp.* VS8 cells before the bioclogging/biocementation procedure, leaving

the urease activity of the dead cells at an acceptable levels for bioclogging, *i.e.* at least 0.1 mM hydrolyzed urea/min, but preferably 1 - 5 mM of hydrolyzed urea/min.

Treatment of bacterial cells in a culture liquid of strain *Yaniella sp.* VS8 has been performed with the aim of killing the cells yet leaving the urease activity of cells intact. Thus, different methods that disrupt the cell membrane but do not significantly destroy the hydrolytic activities of enzymes have been tested. The best results were obtained when a 0.5% solution of sodium dodecyl sulfate surfactant was used for 16 h. The average urease activity for long term incubated dead cells and untreated bacterial cells in a 1 M solution of urea were almost the same. Sand treated with dead but urease-active *Yaniella sp.* VS8 cells (after 9 treatments) caused a hydraulic conductivity drop of from 5.2×10^{-4} m/s to $2.9 \cdot 10^{-8}$ m/s with the contents of precipitated CaCO_3 in the sand at 15% (w/w). Thus, application of safe pure bacterial culture with additional killing of bacterial cells, leaving their urease activity intact, can resolve the biosafety issue for the biocementation/bioclogging of porous materials. However, bacterial biomass production usually employs an expensive broth medium.

7. ACTIVATED SLUDGE FROM MUNICIPAL WASTEWATER TREATMENT PLANTS USED AS RAW MATERIAL

Activated sludge produced in a wastewater treatment plant was evaluated for use to grow urease-producing bacteria *Sporosarcina pasteurii* ATCC 11859 [5]. The sludge was treated with 0.5M NaOH for 20 min followed by neutralization to pH 8.0 with H_2SO_4 . However, the hydrolysate did not sustain UPB growth. Thus, the majority of researchers still use expensive microbiological media with addition of urea after cold sterilization by filtration. This technique is not suitable for large-scale UPB cultivation in cases of practical use for biogrouting and biocementation.

Activated sludge from a municipal wastewater treatment plant (MWWTP) was tested as a possible source of nutrients for UPB. The sludge was settled down and the precipitate was hydrolyzed using 3 ml of concentrated sulfuric acid per 100 ml of precipitate for 1 h at 80°C. The hydrolysate of the activated sludge (HAS) was neutralized to the pH value of 8.0 with 5M NaOH, and supplemented with NaCl, 20 g/l. The medium was not transparent and presented many suspended biomass flakes. This medium, 100 ml, was placed in each of three 300 ml conic flasks. Nothing was added to flask 1. A solution of NiCl_2 , 24 mg/l, was added to flasks 2 and 3. Glucose, 3 g/l, was then added to flask 3. No urea was added to the *Bacillus sp.* VS1 cultivation medium. A sterile solution of urea, 20 g/l, was added to the medium for cultivation of *Yaniella sp.* VS8. The flasks were then placed in

the shaker system, and bacterial cultivation was conducted at 200 rpm with the temperature at 25°C.

The most often used sources of carbon and energy for cultivation of urease-producing bacteria are yeast extract [5, 22, 40] and tryptic soya broth [8, 10]. The best medium for growth of *Yaniella* sp. VS8 (while maintaining urease synthesis) is yeast extract at a concentration of 20 g/l. However, such media are still too expensive for large scale applications.

The cell concentration of urease-producing bacteria *Yaniella* sp. VS8 grown in the medium from hydrolyzed activated sludge (HAS) was almost the same and even a little bit higher than the cell concentration in the medium with 4% of yeast extract (YE). Urease activity in the HAS medium was lower than in the YE medium. The reason of this phenomenon may be the inactivation of urease by proteases produced during bacterial growth in the protein-containing medium. The urease activity of the liquid *Bacillus* sp. VS1 culture grown in HAS medium was reduced significantly in comparison with the YE medium. The possible explanation is that this strain synthesized both endocellular and extracellular urease, and inactivation of urease by the liquid culture proteases was faster. Addition of glucose, 0.3%, or Ni salt did not significantly change either liquid culture urease activity or bacterial growth yield. However, cells of the strain *Bacillus* sp. VS1, growing in HAS medium or HAS medium with addition of glucose, for 24 h in the solution of 1M urea respectively hydrolyzed 45% and 72% of the initial urea.

Cultivation of urease-producing bacteria *Yaniella* sp. VS8, and *Bacillus* sp. VS1 for large-scale biocementation/bioclogging applications might be conducted using a cheap medium derived from Hydrolyzed Activated Sludge (HAS) from municipal wastewater treatment plants. The strain *Bacillus* sp. VS1, which synthesizes constitutive urease, grows well in HAS medium without addition of urea and presents sufficient urease activity for biocementation/bioclogging. Cultivation of the strain *Yaniella* sp. VS8 in HAS medium can be conducted without addition of urea but urea has to be added after cultivation to induce urease synthesis. Urease can be induced during the biocementation/bioclogging process in the calcium salt and urea solution.

8. DRY AND LIQUID CALCIUM-BASED BIOCEMENT

If calcium chloride is to be used as a major component of the dry biocement, to avoid significant heat release during dissolution of the biocement in water before application, it must be calcium chloride dihydrate. If urea is used as a second component, its molar ratio should be slightly higher than stoichiometric ratio to calcium of 1:1. Dry biocement must be standardized by urease activity produced

10 min after dissolution of the biocement in water. It can differ by application, but the levels should be approximately between 0.1 mM/min to 1 mM/min after dissolution of the biocement in water.

Applications of biocement can occur in one or two steps. Treatment in two steps includes addition of a component A (bacteria) for 0.5 h to 2 h for adsorption of cells onto the surfaces, and then treatment for 2 h to 24 h with component B containing concentrations of calcium salt and urea at respective levels of 0.5 M to 1.5 M and 0.75 M to 2 M; is needed in cases where: (i) the bacterial agent form aggregates in calcium salt solutions; (ii) the urease activity of the bacteria is too high (and a significant quantity of calcium will be precipitated in the solution and not on the biocemented surface).

Liquid biocement is a bacterial suspension injected into a soil together or separately using a calcium salt and urea solution. Biocementation can be performed as: (i) a surface percolation using liquid biocement [8, 39]; (ii) spraying of liquid biocement onto the surface [8, 10], or (iii) bulk biocementation through an injection of liquid biocement [15]. These treatments produce different results (see Fig. (1)): a crust on soil surface due to percolation (Fig. 1a), a biocemented layer of defined thickness due to spraying (Fig. 1b), and a biocemented monolith due to injection (Fig. 1c).

9. UNCONFINED COMPRESSIVE (UC) STRENGTH OF SAND AFTER MICP

The calcium carbonate crystals produced from calcium salt and attached to sand surfaces or rock (as a result of biocementation) are an environmentally-neutral substance that can significantly increase the soil strength of fractured rocks; the effect depends on the amount of calcium mineral produced (Fig. 2).

The lines represent mean (dashes) and minimum (dots) values for different types and sizes of sand grains.

Unconfined compressive strength (mean) ($Y_{\min}$, MPa) of biocemented sand depends on the content (% w/w) of precipitated CaCO_3 (X), following Equation 7:

$$Y_{\min} = 0.15X, \text{ if } X < 20 \quad \text{and} \quad Y_{\min} = 3 + 4(X - 20), \text{ if } X > 20 \quad (7)$$

These data can be conventionally interpolated using two lines. Hypothetically, the differing slopes of the lines can be explained by the larger quantity of CaCO_3 needed at the beginning of biocementation to fill in the big pores, and the much

smaller quantity of CaCO_3 needed at the end of biocementation to fill in the remaining narrow channels.

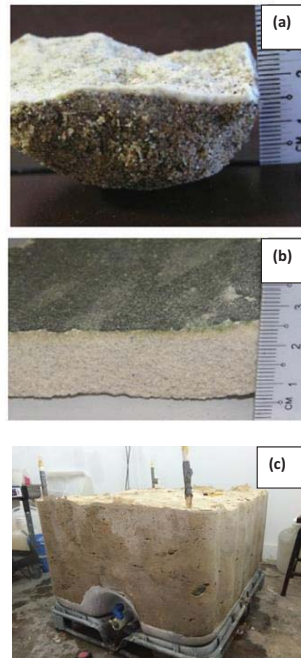


Fig. (1). Different spatial representations of biocementation: **(a)** formation of a crust on a sand surface, **(b)** formation of the biocemented layer at the defined thickness, and **(c)** bulk biocementation of sand.

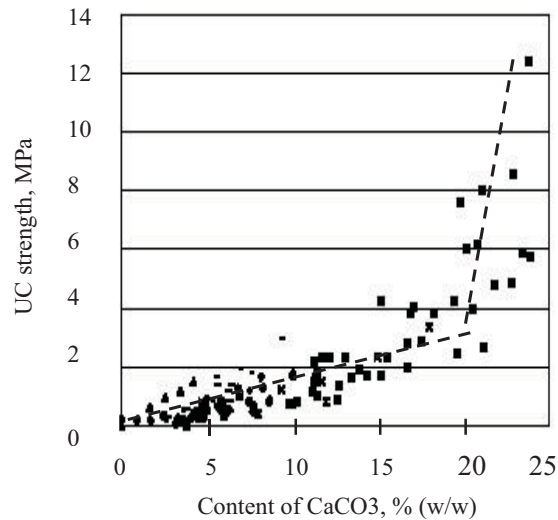


Fig. (2). Unconfined Compressive (UC) strength of sand after MICP [15].

10. ENGINEERING APPLICATIONS OF BIOCEMENTS

A major advantage of biocements is the low viscosity of their solutions and, as a consequence, their deeper penetration into the soil. Biocementation of porous soil and fractured rocks can be used:

- i. to remediate the cracks in concrete and rocks and increase of the durability of concrete structures [27, 41, 44 - 46];
- ii. to enhance the stability of the slopes and dams [42, 59];
- iii. for road construction and prevention of soil erosion [5, 6, 15, 43];
- iv. for the construction of channels, aquaculture ponds, or reservoirs in sandy soil [18];
- v. for sand immobilization and suppression of dust [9, 43];
- vi. to reinforce sand in near-shore areas [47];
- vii. for concrete self-remediation [27, 44, 48, 49];
- viii. for consolidation of porous stone [50] and recycled concrete aggregates [51, 52];
- ix. to decrease fractured rock permeability [15, 53];
- x. for dust suppression and aggregation of fine particles [9, 43, 54];
- xi. for construction of ponds and channels [18];
- xii. to mitigate earth quake-caused soil liquefaction [11, 55];
- xiii. for encapsulation of soft clay [56];
- xiv. for cementation of soft ground and loose soil [57]; and
- xv. for coating of surfaces with calcite/aragonite to enhance marine epibiota colonization, and for the construction of artificial coral reefs [36].

Many new applications for biocements and other eco- energy-efficient biomaterials will be developed in the future [58].

CONSENT FOR PUBLICATION

Not applicable.

CONFLICT OF INTEREST

The authors confirm that this chapter contents have no conflict of interest.

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Interaction Between Natural Fibres and Synthetic Polymers

Alejandro Manzano-Ramírez^{1,*}, Mario Villalón² and José Luis Reyes Araiza³

¹ CINESTAV-Querétaro, Libramiento Norponiente # 2000, zipcode 76230, Fraccionamiento Real de Juriquilla, Querétaro, Qro, México

² Centro de Ingeniería y Desarrollo Industrial (CIDEI), Av. Playa Pie de la Cuesta, No. 702, Desarrollo San Pablo, zipcode 76125, Santiago de Querétaro, Qro, México

³ DIPFI, Facultad de Ingeniería, Universidad Autónoma de Querétaro, C. U. Cerro de las Campanas, Centro, Querétaro, Qro, zipcode 76010, México

Abstract: Lignocellulosic fibers are obtained from agriculture (60%) and forests (40%) industry. Tropical countries produce high amount of these fibers as a by-product. The use of natural fibers is interesting due to their biodegradation capabilities as well as their damping properties, low density and moderate strength. Hence, in the present chapter, the facts due to which natural fibers can be used as reinforced polymers along with the importance and role of the interfacial region will be discussed. In addition, the effect of incorporating chopped natural fibers of different length, as disperse reinforced phase, on the dynamic or quasi-static elastic modulus of glass fiber laminates will be analyzed. A glass fiber composite material model used as a coir fiber effect test bed and a simple, easy and sensitive cantilever experimental setup were validated which are presented with comparative results.

Keywords: Composite Material, Hybrid Material, Mechanical Property.

1. INTRODUCTION

In 1930, the composites began to be an alternative to the substitution of steel, aluminum, concrete or wood, in applications where requisitions and mechanical properties are not very high because these materials can take many forms, underweight or thermal insulation.

* Corresponding author Alejandro Manzano-Ramírez: CINESTAV-Querétaro, Libramiento Norponiente # 2000, zipcode 76230, Fraccionamiento Real de Juriquilla, Querétaro, Qro, México; Tel: +524422119918; E-mail: amanzano@cinvestav.mx

These materials consist of three phases: the continuous phase or matrix, the discontinuous called inclusion and a region generated between both, which is called interfacial region.

The properties of composite materials are strongly influenced by the properties of their constituents, their distribution and interaction between them. The size, size distribution, the shape of the dispersed phase and physicochemical properties play an important role to determine the degree of interaction between the inclusion and the matrix.

The strengthening mechanism depends strongly on the geometry of the reinforcement. A fiber is characterized in that its length is much greater compared to its cross section. The fibers, due to small cross section, are not used directly but are embedded in a matrix to form fibrous compounds. The binder matrix serves to keep the fibers together, protect against environmental degradation, damage during handling and transfers the forces to the fibers across the interface.

The properties of the interface are different from the matrix and reinforcement, because that result from the interactions between both components; so the nature of the matrix-reinforcing interactions plays an important role in the performance of composite materials. There are different interactions that can occur between a parent and inclusion, which provide the composite material a good degree of adhesion, among which are as follows:

- i. Physical interactions: dipole-dipole, induced dipole and dispersion
- ii. Chemical interactions and
- iii. Mechanical interaction.

The interfacial region is of great importance because of its capability to charge transfer into the composite material. Good adhesion at the interfacial region results in a high interfacial stress and therefore an efficient charge transfer. This is only achieved if the fibers are distributed finely and well dispersed in the matrix with which there will be a strong adhesion between the fiber and the matrix.

2. REINFORCED COMPOSITE MATERIALS WITH NATURAL FIBERS

Composite materials properties such as high strength-to-weight ratio, stiffness-to-weight ratio, and corrosive resistance are interesting for high-performance applications in industries such as the automotive, aerospace, defense, and sport goods. Natural fibers have gained interest as composite material reinforcement, for their mechanical properties, lightweight and environment-friendly characteristics such as low energy utilization, renewability and biodegradability [1].

Hybridization of natural and synthetic fibers has improved natural reinforced composites, mechanical properties with a positive impact on environment and costs. 4 billion tons of lignocellulose fiber is produced each year with poor reuse and negative environmental impact [2, 3].

There are countless studies on the reinforcement of polymers using natural fibers, as is the case of the investigation by Shibata *et al.* [4] who produced composites with regenerated cellulose and biodegradable polyesters (hydroxybutyrate-co-3-hydroxyvalerate, polybutylene succinate (PBS) and polylactic acid (PLA)) fabrics. They found that the mechanical properties increase with increasing fiber content and that the compounds of PLA / cellulose increase the biodegradation rate.

In addition to using natural fibers that may have a commercial use, as in the case of sisal, agricultural wastes have also been used like straw and stalk of wheat and corn cobs, Panthapulakkal S. and Sain M [5]. who used such materials as reinforcement of high density polyethylene (HDPE). Other agro-wastes like sugarcane bagasse and other natural fibers from different plants have been used as reinforcing materials.

In addition to agro-wastes, plants harmful to the agriculture have been used as in the case of velvetleaf [6]. Velvetleaf composite materials study demonstrates that these are high quality fibers and widely available in the surrounding making its use feasible in reinforced plastics.

Another example of agricultural waste used in the preparation of composite materials is coconut fiber also called coir fiber. Wang and Huang W. G [7]. reinforced rubber with coir and found that the length of the bio-fiber reinforcement has a significant effect on materials properties and that 60% volume percentage yields better results.

A comparison of the mechanical properties and stress impact, along with water absorption of unsaturated polyester with chontaduro (*gasipaes bactris*) as fiber reinforcing material was presented by Farias *et al.* [8]. This study investigated the effect of two-dimensional orientation of the fibers of the stem and leaf tissues concluding that adding 5mm thickness chontaduro increased impact resistance in 157% compared to polyester resin. Furthermore, compounds in which chontaduro powder is used increased both the tensile strength and moisture absorption.

Cotton has been also used in a fiber reinforced polymer [9], verifying that the mechanical properties increase with increasing fiber content and the addition of reinforcement does not significantly influence the crystallinity or the thermal stability of the composite.

Beg and Pickering [10] studied the effect of hygrothermal aging matrix composites polypropylene (PP) reinforced with virgin and reprocessed fiber radiata pine composites. They found that the diffusion coefficient and the equilibrium moisture content of the compounds decreased as the material is reprocessed. After this aging, the tensile strength, modulus and hardness of both virgin and reprocessed composites decreases while impact resistance and deformation to failure increased.

In addition to the studies on polymers reinforced with a variety of natural fiber, effect of a hybrid reinforcement with at least two bio-fibers was also analyzed, as done by Paiva [11]. These authors studied the variation between the volume fraction of fiber cotton / ramie and ramie fiber orientation on tensile properties of the compound. Orientation of ramie fibers parallel to the axis of tension has the highest tensile properties.

Indicula *et al.* [12] also used two different bio-fibers (banana and sisal short fibers) as reinforcing polyester materials. The composites were produced by impregnating process and compression molding in which the volume percent of the fiber and the variation in banana to sisal fiber ratio were studied.

Tensile properties of sisal, coconut spathe and ridge gourd reinforced epoxy resin composites increased with the weight fraction of fibers to a certain extent and then decreased [13]. Random oriented coir fiber–polyester composites showed poor coir reinforcement performance attributed to a low modulus of elasticity reaching flexural strengths suited for non-structural building elements [14]. Short Bagasse/Coir hybrid fiber reinforced epoxy properties depend on fibers aspect ratio, orientation, dispersion and polymer's interaction strength [15]. Tensile strength, tensile modulus and flexural strength increased with increasing fiber length up to 30 mm (13.05 MPa, 2.064 GPa and 35.42 MPa respectively) in coir-reinforced epoxy composites [16]. Harish *et al.* reported average values for the tensile strength (17.86 MPa), flexural strength (31.08 MPa) and impact strength (11.49 kJ/m²) of coir/epoxy composites [17].

The mechanical and dynamic mechanical properties of short bagasse/coir hybrid fibers reinforced epoxy novolac composites resulted in higher tensile modulus for the tri-layer pattern (bagasse/coir/bagasse) showing a maximum stiffness in comparison to other arrangements [17]. High mechanical properties were obtained in coir/polyester fiber content 19 to 29-wt % [18]. Physical, mechanical, and flammability properties of 10 mm thick coconut fiber reinforced Polypropylene (PP) composite panels were investigated for different coir fiber content loading, showing better mechanical properties at 60-wt % coir fiber [19]. Another study however reported that 30-wt % coir fibers reinforced PP composites had the

optimum set of mechanical properties over different palm and coir content loading [20]. Different natural fillers like crab carapace and coconut shell particles were also tested and showed better mechanical properties in coir-polyester and coir-polypropylene composites respectively [21, 22].

Carbon fibers or glass fibers are used in the same polymeric resin matrix to form hybrid composites to produce material that suits various requirements. Pavithran *et al.* (1991) compared the coir-reinforced composite with coir- glass fiber hybrid composite under weathering test and reported better flexural and interlaminar shear strength of laminate arrangements made of coir core with mat glass shells [23]. Jayabal *et al.* (2011), reported that 3-layer glass-coir hybrid polyester composites exhibited average tensile strength values of 52 MPa while the average tensile strength of 2-layer woven coir/polyester composites was found to be 34 MPa. Two layers of woven glass plies at one extreme and coir mat (GGC) exhibited better mechanical properties than two extreme woven glass plies (GCG) and two extreme coir plies (CGC) [24]. Bhagat *et al.* (2014) tested different coir content loading and fibers length in coir/glass hybrid composite and obtained maximum strength properties (18 MPa) with 10 wt% coir fiber loading at 15 mm length, maximum flexural strength (63 MPa) for 10 wt% coir fiber loading at 15 mm fiber length, maximum hardness (21.3 Hv) with 10 wt% fiber loading at 20 mm fiber length. The tensile modulus increased with the fiber length, irrespective of fiber loading [25]. Muthu *et al.* (2016) reinforced glass and coir fiber hybrid composite with different content loading of carbon nano fibres (CNFs) showing that 0.5 wt% functionalized CNFs had better mechanical properties than 0.1 and 1 wt% of CNFs. “At higher weight fraction than 1 wt% CNFs, agglomerations could not be prevented and this led to poor mechanical properties” [26].

2.1. Natural Fibers

Depending on its origin, natural fibers can be grouped into: stem fibers (jute, banana, flax, hemp, kenaf, mesta), leaf fibers (pineapple, sisal, sisal, *etc.*) and fruit fibers (coconut, cotton, oil palm). Such fibers consist of cellulose (α -cellulose), hemicellulose, lignin, and pectins fat [27]. In Fig. (1), main parts of a bio-fibre are shown.

Cellulose is a natural polymer consisting of repeating units of D-anhydroglucose ($C_6H_{10}O_5$) attached *via* 1,4-b-D-glycosidic C1 and C4 in positions [28]. Each repeating unit contains three hydroxyl groups. Each of the monomers that form contains three hydroxyl groups which, due to links forming hydrogen bridge, play an important role in crystallinity, governing the properties of cellulose. Such material form microcrystalline structures with regions of high order (crystalline) and low order (amorphous). Their morphology is as thin as thin microfilaments

bars. Cellulose is resistant to strong alkali (17.5% W/V) but readily hydrolyzed by water, soluble sugars for example is also relatively resistant to oxidizing agents.

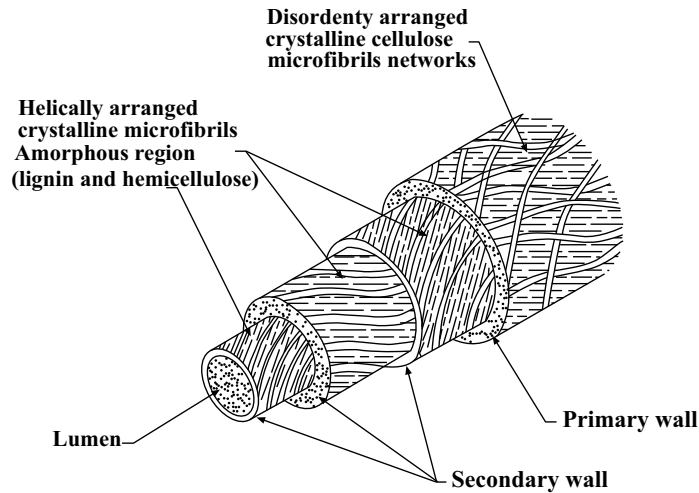


Fig. (1). Structure of a biofibre.

Hemicellulose is a polysaccharides consisting of groups composed of a combination of sugars of 5 and 6 carbon chain, resulting in a very different structure than cellulose. Hemicellulose differs from cellulose in three aspects: first, the hemicellulose is formed by a variety of sugars, while the cellulose chains consists solely of 1, 4-b-D-glucopyranose. Second, it contains lignins which are branched polymers that gives its amorphous nature, whereas cellulose is a linear polymer. Third, the degree of polymerization of native cellulose is about 10-100 times greater than the hemicellulose, which is about 50-300; addition, this polymer is highly hydrophilic, alkali-soluble and readily hydrolyzable in acid [27].

Lignin is a tridimensional aliphatic and aromatic copolymer high molecular weight constituents. It has five hydroxyl groups and 5-methoxy-per repeat unit, and contain carbonyl groups. It is considered a thermoplastic polymer with a glass transition temperature of 90°C and a melting temperature of 170°C. With no crystal structure and a hydrophobic nature, it is responsible for the plants rigidity. It is hydrolysable in acid, not soluble in alkali, easily oxidizable and can be condensed with phenol [29].

Pectin is the name given to a large number of hetero-polysaccharides, which give flexibility to plants. Fats constitute the lower part of the fibers and consist of different types of alcohols.

The structure, microfibrillar angle, dimensions of the cells, defects and composition of natural fibers are the most important variables that determine their properties [30]. Generally, by increasing the cellulose content, the mechanical properties of the fibers increase. The microfibrillar angle determines the stiffness of the fibers. Natural fibers are more ductile if microfibrils are oriented spirally in its axis. If the microfibrils are oriented towards said axis, the fibers become rigid, inflexible with high tensile strength.

However, even when bio-fibres have good mechanical properties, in order to make optimal use of its potential as a reinforcing material it is necessary to vary their hydrophilic character, thus achieving compatibility with the polymer matrices which are to the vast majority hydrophobic. As such difference in physicochemical properties between the natural fiber and thermoplastic matrix decreases, forces transfer between the two results to be more efficient, and therefore, the effective mechanical properties of the composite will improve.

Another disadvantage of natural fibers is their low degradation temperature ($\sim 200^{\circ}\text{C}$), precluding its use as reinforcement of some thermostable materials with high curing temperature, which restricts to composite materials applications where relatively low temperatures are required [31]. One way to increase the adhesion between the natural fibers and polymer matrices and to minimize the inherent disadvantages of these fibers is to perform a chemical treatment.

Coir is a cheap fiber, even cheaper than sisal and jute [32]. It is a lignocellulose fiber found in the fibrous mesocarp of coconuts outer shell, or husk that can be stretched beyond its elastic limit without rupture due to helical arrangement of micro-fibrils at 45° [33]. Of all natural fibers, coir has the lowest thermal conductivity and bulk density [34], and the best relative waterproof and resistance to salty water. Reported coir fiber's composition is 43% cellulose, 0.25% hemicellulose, 45% lignin, 3% pectin and residual gums [35]. Reported characteristics include: 200 ± 10 μm diameter, 144.6 MPa tensile strength, 3,101.2 MPa Young's modulus, $32.3 \pm 0.2\%$ elongation at break, and 100 ± 5 aspect ratio (L/D) [36]. Coir fibers are less brittle than glass fibers, can be chemically modified, are non-toxic and are biodegradable, but unfortunately the performance of coir as a reinforcement in polymer composites is unsatisfactory and not comparable even with other natural fibers. This inferior performance of coir is due to various factors such as its low cellulose content, high lignin content, high microfibrillar angle, and large as well as variable diameter [37].

2.2. Chemical Treatments to Promote Adherence of Natural Fibers

The main drawback of natural fiber/polymer composites is the inherent in

compatibility between hydrophilic lignocellulose fibers and hydrophobic polymeric matrices resulting in composites with low mechanical properties due to lack of adhesion between the fibres and the resin at the interface [38].

There are various chemical treatments that promote adherence of natural fibers (bio-fibers) with the polymer matrix, among which the alkali treatment and using coupling agents such as titanates, organo-phosphorus compounds, halogenating agents' acids, zirconates, silanes, and others.

There are numerous studies on the effects of different coupling agents on the mechanical properties of composites with natural fibers reinforcement. One example is the use of potassium permanganate (KMnO_4) and benzoyl chloride [39]. Recently, natural coupling agents such as zein, which is a maize protein and used by Maya *et al.* [40] to compatibilize flax and to use it as PP reinforcement, has been studied. Alkali treatment of cellulosic fibers, also called mercerizing, is usual to produce high quality fibers to improve fiber-matrix adhesion due to removal of natural impurities (lignins, pectin, hemicellulose and waxy compounds) and artificial ones that are on the surface, changing the crystalline structure of cellulose [41]. Besides the above, the fiber diameter is reduced [42] and fibrillation is enhanced which favors the development of a roughened surface [43] and as result the aspect ratio is increasing and an improvement in the mechanical properties of the biofiber is obtained. Due to hemicellulose removal, the inter-fiber region becomes less dense and rigid and hence the individual fibrils can be accommodated in such a way that free spaces are created where the matrix can penetrate [44].

Alkali treatment induces changes in the physicochemical properties of the fibers of sisal [45] having a partial dissolution of the hemicellulose, lignin and pectin.

The coupling agents are organometallic compounds containing organic and inorganic groups that are capable of binding two different surfaces by forming chemical bonds. In Fig. (2), a schematic of how a coupling agent acts as a bridge between the polymer matrix and the fiber is shown.

The incorporation of these additives modify the physicochemical and mechanical properties of the fiber-matrix interfacial region increases as the degree of adhesion between the two components, whereby the mechanical properties of the composite material increases.

The polymer chains of the silane can adhere to the matrix by Van der Waals forces. As a result, the coupling silane compound forms a bridge between the interface of the natural fiber and the polymer matrix, acting as a compatibilizer [39, 46] in addition to inorganic or organic surface protection.

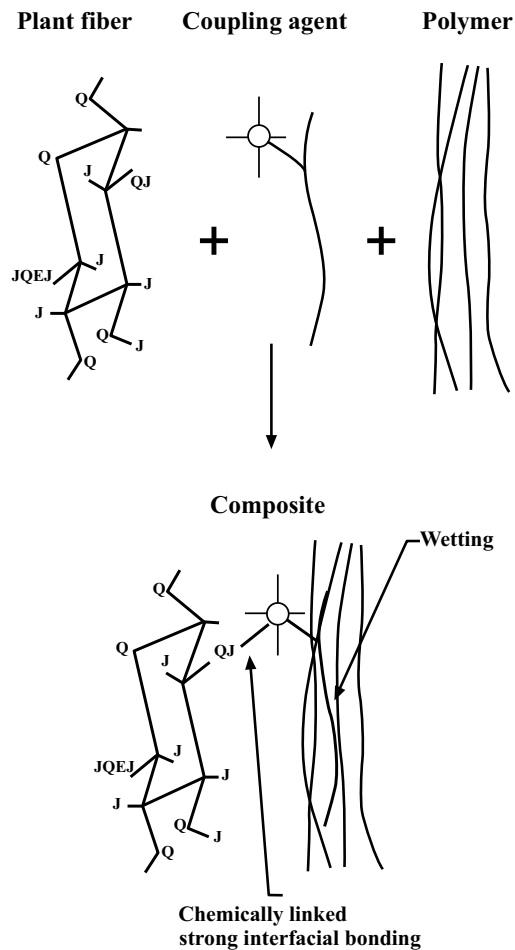


Fig. (2). Mechanism coupling agent between the hydrophilic fiber and the hydrophobic polymer matrix.

Bond formation of the silane with the inorganic substrate is influenced by different factors such as the silicon functional group, which affects the wetting properties and the reaction rate, the organo functional group that affects the wet and the properties of film formation. Additives, solvents, formed films, catalyst (acids or bases), *etc.*, affect the binding of silane and the reaction rate.

Reaction mechanisms organo-functional silanes are summarized in the following steps:

- i. Reaction silico-functional group:
 1. Hydrolysis silico-functional group to form silanols;
 2. Link with inorganic or organic surface silanol; and

3. Condensation between the silanol and hydroxyl groups of the inorganic or organic surface.

ii. Reaction organo-functional group:

1. Link with the polymer.

The incorporation of these additives modify the physicochemical and mechanical properties of the fiber-matrix interfacial region so that the degree of adhesion between the two components is increased and this results in an improvement in the mechanical properties of the composite [47]. In Fig. (3), the interaction between the coupling agent and the cellulosic fiber is observed.

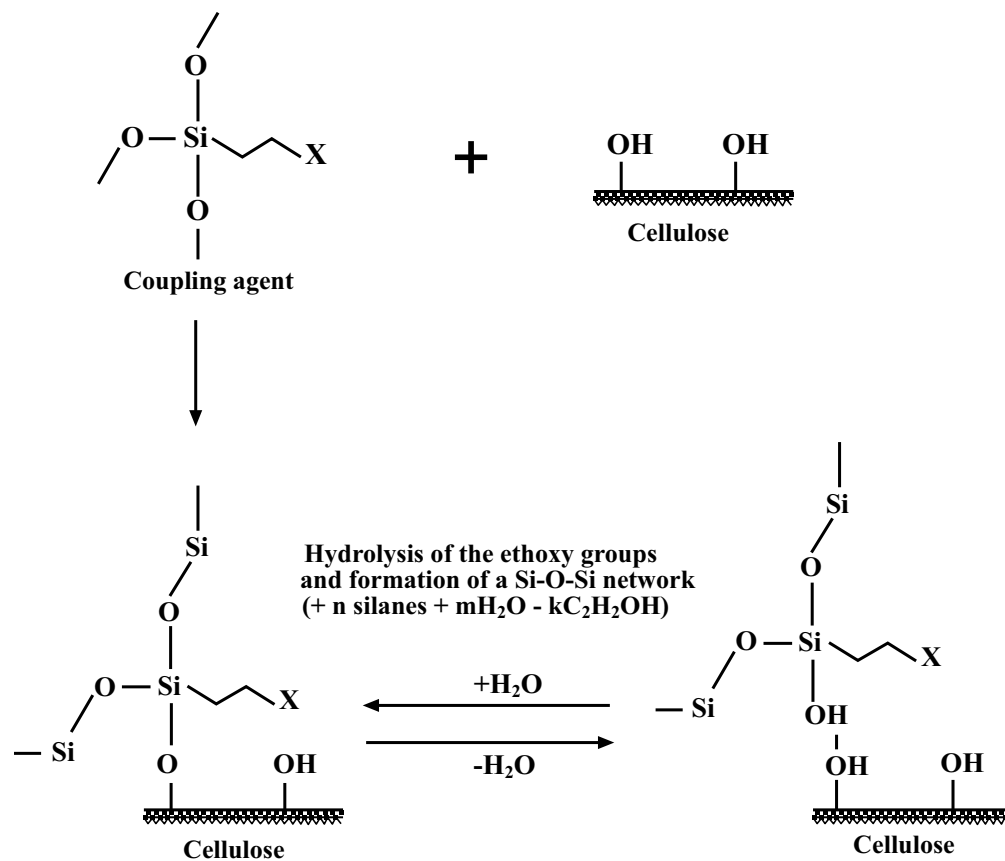


Fig. (3). Interaction between the coupling agent and the cellulosic fiber.

3. TESTING STATIC METHODS

Since the use of bio-fibers like sisal, henequen, jute, hemp, banana, oil palm, wood pulp as a reinforcement in polymer matrix has gain importance [48 - 51],

brief examples of tensile and flexural testing test are presented.

According to the recommendation of ASTM standard D3039 [52] and ASTM D6272 [53], tension and flexural test specimen are cut from the hybrid laminates composites. Specimens 250 mm length and 25 mm width are used, moreover the distance between the tabs (gage length) was 150 mm. On the other hand, for flexural tests specimens 127 mm length and 12.7 mm width are used.

Tensile tests were carried out on a Tinius Olsen universal testing machine equipped with a 3,000 kN load cell and the cross-head speed used was 5 mm/min. The tensile strength in MPa was calculated by dividing the breaking load in Newton's by the original minimum cross-sectional area of the specimen in square millimeters. The ultimate stress and the ultimate strain were recorded when the specimen were broken, (Figs. 4 and 5).



Fig. (4). Tensile test of biocomposite with natural fiber fabric.



Fig. (5). Tensile test of biocomposite with longitudinal unidirectional natural fiber.

The average values of tensile strength and modulus of elasticity for different laminates and stacking sequences are summarized in Table 1. To compare, test results correspondent to specimens reinforced with just 10 layers of glass fiber fabric (10G), 10 layers of henequen fiber fabric (10H), and the substitution of glass fiber layers for henequen fiber (H), 9G1H, 8G2H, 7G3H, 6G4H, 5G5H, are presented in Table 1. It is well known that the tensile strength of the composite is influenced by the strength modulus of the fibers and interfacial bonding due to wettability of fibers. From the result, it may be observed that the tensile properties decrease as the number of layers of henequen fabric increases. However, it can be seen how with ten layer of henequen fabric, an eco-friendly epoxy composite with good mechanical strength is obtained, since the mechanical anchoring of the knots increased. Fig. (6) shows the SEM micro-graphs of a henequen fabric.

Table 1. Tensile mechanical properties of hybrid reinforced (glass-henequen fiber) epoxy.

Sample	10H	10G	9G1H	8G2H	7G3H	6G4H	5G5H
Tensile strength (MPa)	49.1	156.2	140.0	131.1	122.2	96.79	60.79
Total deformation (%)	0.8	5.3	5.1	5.0	5.0	4.3	2.7
Elastic modulus (GPa)	2.4	3.18	2.97	2.91	2.9	2.63	2.3
Poisson modulus	0.28	0.3	0.29	0.29	0.29	0.28	0.28

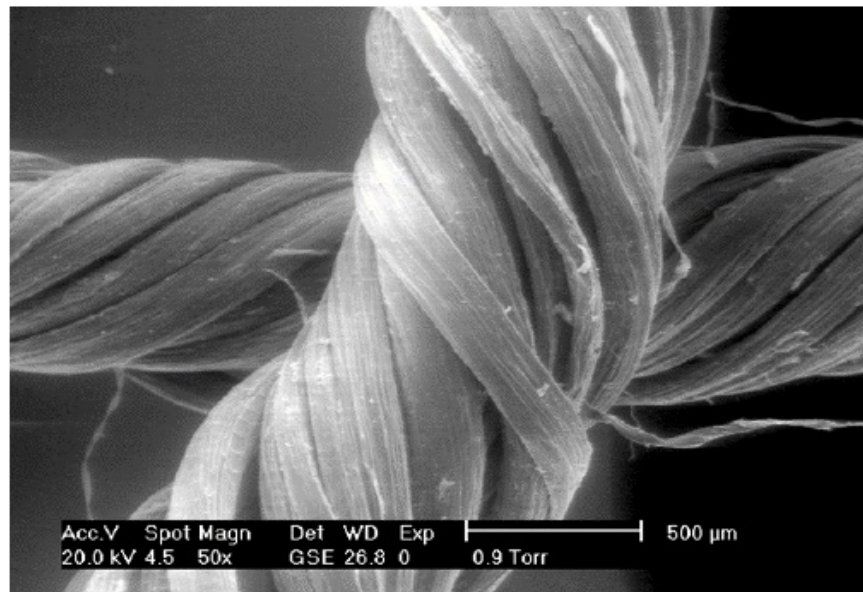


Fig. (6). Henequen fibers.

Henequen fabric exhibits a suitable mechanical anchoring due to the additional knot in the henequen fabric. However, hybrid compounds have lower mechanical properties. This result may be associated with the lower mechanical properties of natural fibers compared to glass fibers, and to a decrease in the wettability of large amount of natural fiber. Fig. (7) shows the stress-strain curve of a specimen with ten layers of henequen fabric, it can be observed that there is no plastic deformation. That is, a linear elastic behavior is observed until rupture, without observing the collapse of the specimen at the moment of fracture when the maximum stress is reached.

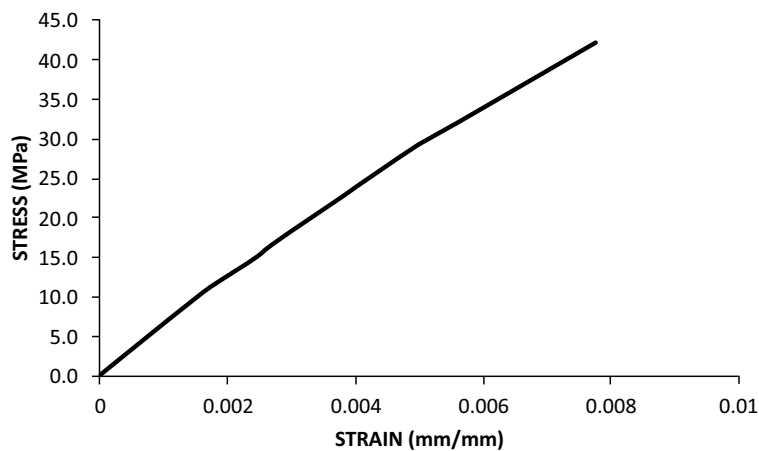


Fig. (7). Tensile stress-strain curve for ten layer of henequen fabric.

According to ASTM standard D6272, flexural test specimens were performed in four-points bending with a recommended span to depth ratio of 16:1. The test was conducted on the same machine using 2.8 mm/min rate of loading. The flexural strength was determined in base of Equation:

$$\sigma = PL/bh \quad (1)$$

where: P is the maximum load at failure (N), L is the span (mm), b and h is the width and thickness of the specimen (mm), respectively.

The flexural modulus is calculated from the slope of the initial portion of the load-deflection curve. Flexural modulus is given by Equation 2:

$$E = (mL^3)/(4bh^3) \quad (2)$$

where: “ m ” is the initial slope of the load deflection curve.

The average values of flexural strength and modulus of elasticity for laminates with different stacking sequences are presented in Table 2. The specimen was deflected until rupture occurs in the outer surface of the test specimen (zone of the maximum tensile stress) but without collapse Fig. (8). From the result, it can be seen that the flexural properties show the same trend as the tensile properties *i.e.* they decrease as the number of layers of henequen woven fabric is increased. In the flexural stress-strain curve it can be observed a linear elastic behavior until rupture, without collapsing at the moment of fracture when reaching the maximum stress (Fig. 9). This is due to the action of the reinforcement in the tension zone.

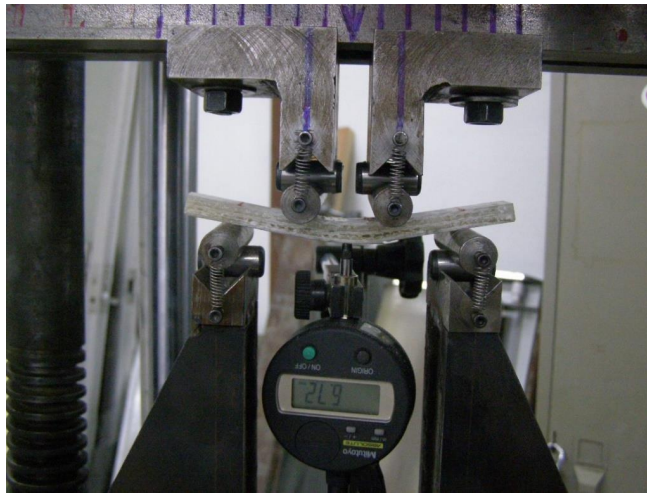


Fig. (8). Flexural test of biocomposite.

Table 2. Flexural mechanical properties of hybrid reinforced (glass-henequen fiber) epoxy.

Sample	10H	10G	9G1H	8G2H	7G3H	6G4H	5G5H
Tensile strength (MPa)	53.5	128.6	124.2	104.6	111.9	98.6	80.65
Strain (%)	1.2	1.85	1.65	1.47	1.48	1.3	1.34
Elastic modulus (GPa)	5.4	11.4	11.0	8.9	8.38	7.3	6.96

Fig. (10) is the SEM micro-graphs of the cracked zone of a specimen tested in flexion in which it may be observed the phenomenon of debonding and pull-out, Hence the fiber was broken in the polymer matrix due to mechanical anchoring induced to the additional knot in the henequen fabric. However, although the nodes induce a good anchorage, they also induce areas of stress concentration, which may induce a decrease in the mechanical properties and a non-linear mechanical behavior due to discontinuities (*e.g.* knot, change of the material,

change of the geometry, *etc.*) alters the stress distribution in the neighborhood of the discontinuity.

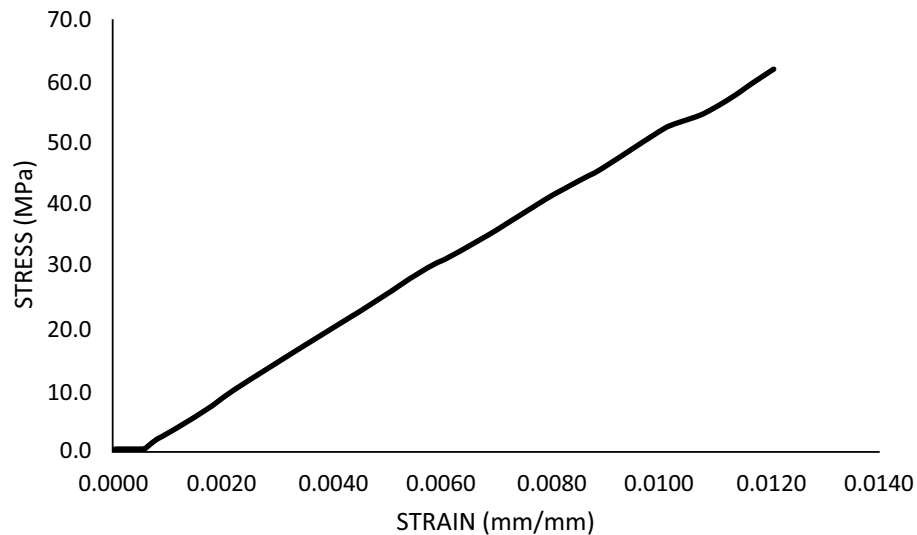


Fig. (9). Flexural stress-strain curve for four-points bending-tens layer of henequen fabric.

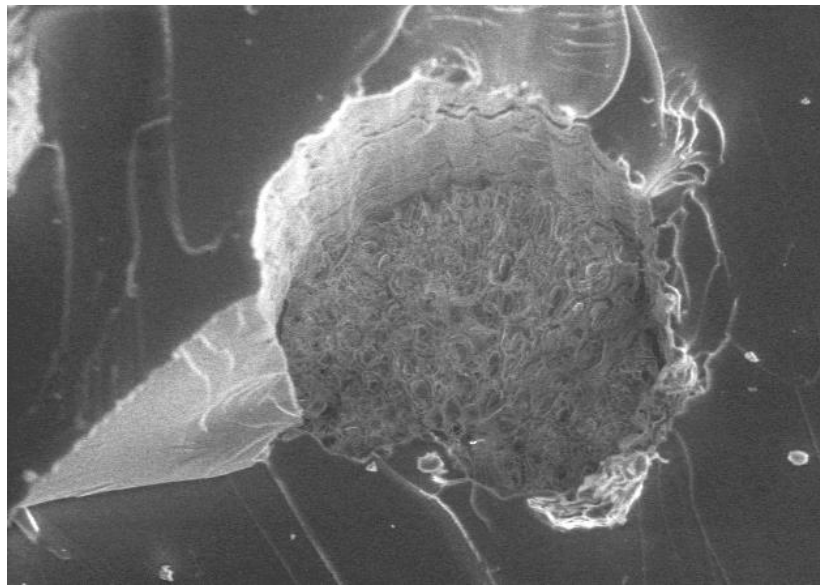


Fig. 10. Cross section of natural fiber in biocomposite: flexural test.

In relation to the stability or failure mode of the biocomposite, from the toughness point of view, the occurrence of fiber bridging and pull-out during crack growth is highly desirable.

3.1. Conclusions of Static Tests

The tensile and flexural strength of the composite is influenced by the strength, modulus of the fibers, and interfacial bonding through the anchor of the fibers. From the result, it is may be observed that the tensile and flexural properties of the hybrid reinforced epoxy composites, increases as the number of layers of henequen fabric decreases. This result may be associated to the lower mechanical properties of natural fibers compared to glass fibers, as well as to a decrease in the wettability of large amount of natural fiber.

As the fiber weight fraction increase, the wettability of fiber with resin decreases and a weak interfacial bonding occurs.

A strong interface lead to a brittle fracture mode with relatively low energy absorption, whereas a weak interface favors a multiple shear mode with high energy absorption. In some cases, this weak interface is desirable since breaking weak interfaces can act as energy sinks and the toughness of the composite may be increased.

Nevertheless, in the present example an eco-friendly composite material with good mechanical strength was achieved when ten layer of henequen fabric were used, due to an increase in the mechanical anchoring of the henequen fabrics.

4. TESTING-VIBRATION METHODS

Vibration methods are non-destructive, rapid, convenient of use and money saving. The cantilever beam vibration technique allows measuring the elasticity modulus (E_d) and damping by measuring the first natural frequency and amplitudes at different cycles. E_d is the ratio of stress to strain for a material under dynamic load, and indicates stiffness; E_d has been used for control quality purpose in production of wood-based composites [54].

The main objective of this research was to study the effect of untreated and treated coir fiber incorporated in glass fiber reinforced thin epoxy composites on dynamic and quasi-static elasticity moduli. The aim of the study is to prospect composite applications to coir fiber natural properties. So, on the one hand, the coir/glass hybrid composite is compared with the glass fiber control tensile strength and elasticity modulus. On the other, an experimental setup to rapidly assess vibration properties of composite laminates is validated.

4.1. Dynamic Mechanical Analysis (DMA)

The cantilever beam vibration technique allows measuring the elasticity or storage modulus (E_d) and damping rate ($\tan\delta$) by measuring the first natural frequency and amplitudes at different cycles. The storage modulus (E_d) or dynamic modulus is related to Young's modulus (the ratio of stress to strain) for a material under dynamic load and is associated with "stiffness". E_d is regarded as a material tendency/ability to store energy applied to it for future purpose [54].

Loss modulus (E_{Loss}) or dynamic loss modulus is a viscous response of the materials and is regarded as materials tendency to dissipate energy. E_{Loss} is often associated with "internal friction" and is sensitive to different kinds of molecular motions, transitions, relaxation processes, morphology and other structural heterogeneities.

Damping rate ($\tan\delta$) is a dimensionless number defined as the ratio of loss and storage modulus ($\tan\delta = E_{\text{Loss}}/E_d$). High $\tan\delta$ value indicates high, non-elastic strain component while a low value indicates high elasticity. Increase in the fiber/matrix interface bonding results reduction in damping factor as mobility at the fiber/matrix interface decreases.

Saba *et al.* (2016) states that incorporation of treated fiber increases the loss modulus (E_{Loss}) of the composites compared to untreated fiber, consequently increases the structural mobility of the polymer within the composite [55].

The composites reinforced with flax fiber displayed improved damping compared to composites reinforced with synthetic carbon fiber (CF) and glass fiber (GF). In this case researchers find the best compromise between stiffness and damping with flax fiber reinforced in semi-crystalline renewable and biodegradable polylactic acid (PLA) [56]. Sreenivasan *et al.* [57], studied dynamical characteristics of Sansevieria cylindrical (SC) fiber reinforced polyester matrix composites at different temperatures. E_d , E_{Loss} and damping were influenced by the increase in fiber length and fiber loading and declared that damping property of fiber reinforced composite materials depends upon various factors such as fiber/matrix interface, frictional resistance, interphase zone, fiber breakage and matrix cracking. Damping value decreased and storage modulus (E_d) value increased for treated coconut sheath fiber reinforced epoxy composites compared to untreated sheath fiber reinforced epoxy composites indicating higher fiber/epoxy adhesion [58].

4.2. Design of Dynamic Mechanical Tests

A complementary objective of this research was to validate the cantilever beam vibration set up to study damping properties of thin coir/glass fiber hybrid reinforced epoxy composite materials. Cantilever beam vibration technique implemented with an accelerometer [59, 60] and/or a vibrometer was compared after obtaining E_d and damping rate.

4.2.1. Preparation of Treated Short Coir Fibre

Coir fibre was treated with a NaOH aqueous solution (2% w/v) for an hour at 25°C, they were then washed with distilled water until all the sodium hydroxide was eliminated, that is until rinse water no longer indicated any alkalinity reaction. Subsequently, the fibres were dried at 60°C for 24 h. In addition, to the fibre surface treatment, 1% vinyltriethoxysilane (Sigma-Aldrich) weight percentage with respect to the fibre was dissolved for its hydrolysis in a mixture of ethanol/water (90/10 w/w) at 25°C. The pH of the solution was adjusted to 3.5 with acetic acid with continuous stirring for 10 min. Then, the fibres were immersed in the solution and left for 1h under stirring and then dried at 60°C for 24 h.

4.2.2. Composite Materials Fabrication

The composite materials obtained were based on glass/epoxy and glass/coir/epoxy hybrid composite laminate. Square cut-outs of 320 mm² plain weave glass fibre pre-impregnated with epoxy resin (CYCOM 5320/ 12050 in x 40 yd, from CYTEC company) were used in a stacking sequence [0]4. For hybrid composites, treated short length chopped (1-3 mm) of natural coir fibre was placed in the middle of two glass-fibre prepreg double sheets, and laminates were prepared by the vacuum bag technique (4 glass sheets/1 coir layer; Figs. (11A, B, C and D)). Vacuum bags were IPPLON KM1300 60, Breather/Bleeder was Econoweave 44 60in x 100yd., Release Film was WL5200, and bag-sealing tape was AT-200Y 1/8in x 1/2in x 25ft all from AIRTECH COMPANY. Structural Adhesive Film type AF163-2K 060wt 36in x50 yds was purchased from 3M™ Scotch-Weld™. Pre-pregs were placed on an aluminum mould (50in x 50in), which was connected to a single zone hot bonder HEATCON® Composite System, temperature was set up at 40°C while 6 grams of coir fibre were uniformly distributed.

composites (B, C, D, E, F).



A: Plain weave glass fibre.



B: Plain weave glass fibre with 30% (v/v) treated or untreated coir middle layer



C: Plain weave glass fibre with 30% (v/v) extra epoxy middle layer



D: Plain weave glass fibre with 23% (v/v) treated or untreated coir and 26% (v/v) extra epoxy middle layer



E: Plain weave glass fibre with extra epoxy symmetrical layers



F: Plain weave glass fibre with 15% (v/v) short or 40% (v/v) long untreated coir and extra epoxy symmetrical layers

Fig. (11). Layup arrangements of glass fibre (A) and glass/coir hybrid epoxy composites (B, C, D, E, F).

Squares of 32 cm² plain weave glass fibre prepreg with epoxy resin were used in a stacking sequence [0]4. Short and long length chopped untreated natural coir fibres (1-3 mm and 10-20 mm) were placed in between of two glass fibre prepreg sheets then superposed (4 glass sheets/2 coir layers; Figs. 11E and F) and laminates were prepared by the vacuum bag technique as described above. The volume fraction of short and long natural fibre was 15% and 40%, with a mass fraction of 4.7% and 4.3%, respectively.

The specimens were cut-off from the laminate plates at the desired dimensions. Samples of 254 mm length and 25.4 mm width were cut and tested at vibration conditions in a single cantilever beam arrangement. The samples edges were carefully sanded and tensile tested.

4.2.3. Dynamic Test

A cantilever beam specimen was used to perform dynamic tests (Fig. 12). A single-cantilever experimental device was developed to hold one end of a specimen and free at the other end. The vibration frequency and damping ratio of 100 mm long sections of each sample was measured by an accelerometer ADXL335 at z-axis perpendicular to the sample test plane after an average 0.7 N impact with a PCB Piezotronics hammer and red in an oscilloscope (Tektronix TDS 2014B). Vibration frequencies were also measured with a Polytec PDV100 vibrometer allowing comparison of results with or without the accelerometer.

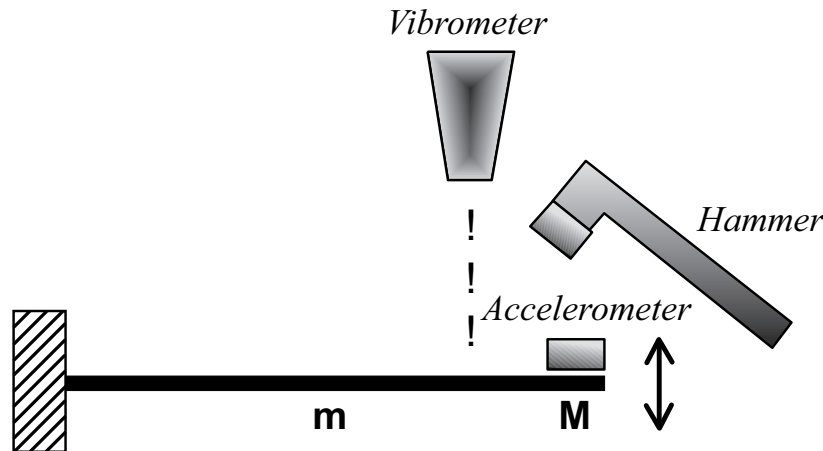


Fig. (12). Single cantilever configuration.

The elastic modulus was estimated with the cantilever mathematical model, Equations 3, 4 and 5 [61]:

$$Ed = \frac{(wn)^2(M + 0.23m)L^3}{3I} \quad (3)$$

$$wn = 2\pi(fn) \quad (4)$$

$$I = \frac{bh^3}{12} \quad (5)$$

where: M = mass placed at the end of the cantilever

m = mass of the composite material sample

w = angular frequency

f = vibration frequency

Ed = dynamic elasticity modulus

I = moment of inertia

b = sample's depth

h = sample's width

L = sample's length

4.3. Coir Fiber Dynamic Test Results

The vibration frequency of plain weave glass fiber reinforced epoxy composite (5.9 Hz) increased 67% when untreated coir fiber was added in the middle layer and 73% when treated coir fiber was added (configurations A and B in Fig. (11)). Dynamic Young's moduli (Ed) calculated with the cantilever model, increased 2.7 and 2.5 times when untreated and treated coir fiber was added at the middle layer, from 6.0 ± 0.5 GPa to 16.3 ± 1.5 GPa and to 15.0 ± 2.1 GPa, respectively (Fig. 13). These results suggest that coir addition at the middle layer increases the elasticity property of the bulk material while treatment with coupling agent had little effect on dynamic Young's modulus (Ed) of glass/coir fibers hybrid composite materials. The vibration frequency of plain weave glass fiber reinforced epoxy composite, increased 52% when epoxy only was added at the middle layer (configuration C in Fig. (11)). When both untreated and treated coir fiber was added with extra epoxy (configuration D in Fig. (11)) an additional increase in frequency was observed, of 35% and 41%, respectively compared to extra epoxy control. Nevertheless, dynamic Young's moduli increased

approximately 1 fold when extra epoxy resin was added to the laminates with untreated (12.2 ± 0.7 GPa), and treated coir fibre (10.4 ± 2.6 GPa), at the middle layer, showing no significant difference with addition of extra epoxy alone (11.8 ± 0.4 GPa) (Fig. 13). Quasi-static elasticity moduli decreased more than 50% for any addition in the middle layer of extra epoxy with or without untreated or treated coir, passing from 17.94 GPa to 9.98 GPa, 8.53 GPa and 8.56 GPa, respectively.

Tensile properties of glass fiber reinforced epoxy composites and glass/coir reinforced hybrid composites were further investigated and their quasi-static tensile stress was compared. Hence, glass fiber epoxy composite tensile stress (347.8 ± 15.8 MPa) was reduced by addition of untreated or treated coir by 38% and 61% respectively. In addition, when extra epoxy resin alone, or with untreated or treated coir, was added yield strength decreased 48%, 64% and 54% (to 180.0 MPa, 126.1 MPa and 160.2 MPa), respectively (Fig. 14).

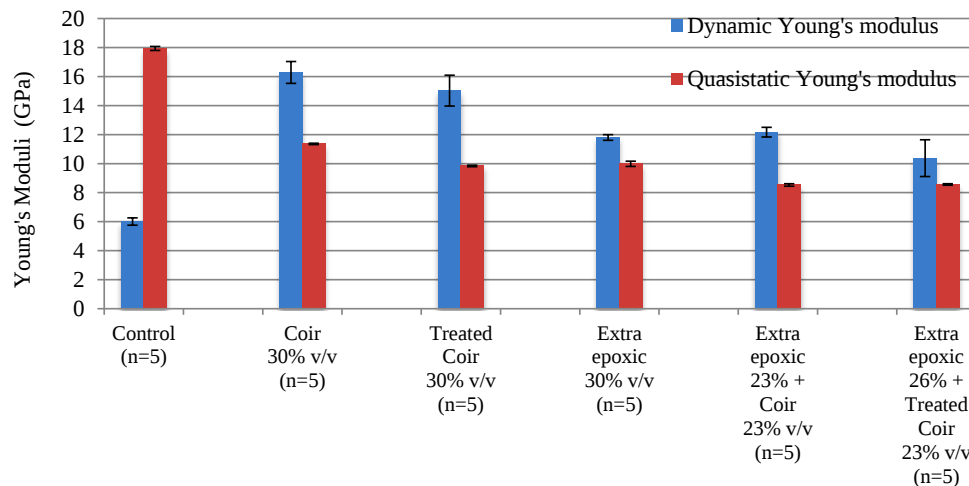


Fig. (13). Dynamic elasticity moduli (GPa) (blue bars) and Quasi-static elasticity moduli (GPa) (red bars) for plain weave glass fiber reinforced epoxy composites (control), and hybrid composites made of 30% (v/v) coir fiber or alkali treated coir fiber, and 23% v/v coir fiber with extra epoxy (23% and 26% v/v, respectively) added in the middle layer.

Failure analysis allowed detecting that delamination in the coir middle layer is the primary cause of fracture in glass/coir fiber hybrid composite in accordance to low coir-epoxy matrix adhesion as reported elsewhere [59 - 62]. In extra epoxy added glass/coir fiber hybrid composite, the fracture initiates in the matrix and the glass fiber, which suggest better-embedded and adhered natural fiber. These

results allow concluding that coir pretreatment doesn't favor adhesion significantly while extra epoxy prevents delamination.

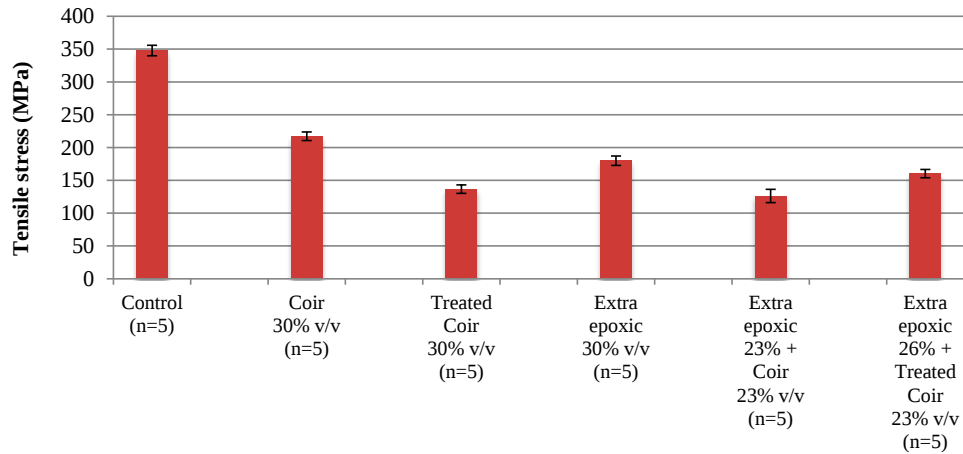


Fig. (14). Tensile stress for plain weave glass fibre reinforced epoxy composites (control), 30% (v/v) untreated and alkali treated coir/glass fibre hybrid composites with or without extra epoxy added in the middle layer.

To further investigate the role of coir fiber length, all following samples incorporated extra epoxy with two symmetrical layers of coir fiber (E and F configurations in Fig. (11)). This second double-layered configuration had glass fiber in its middle layer instead of coir fiber as in the first configuration (glass fiber control) and was used to compare the effect of short or long untreated coir fiber addition.

Vibration frequencies of double-layered coir/glass fibres extra epoxy hybrid composite obtained with the use of an accelerometer, or with both a vibrometer and an accelerometer, or with a vibrometer alone showed consistent variations as compared to the glass fibre extra epoxy control composite (Fig. 15). Results obtained with an accelerometer were 36% and 45% increase for short and long coir fibre, respectively, results obtained with a vibrometer in the presence of an accelerometer were 38% and 45% increase for short and long coir fibre respectively, and results obtained with a vibrometer alone were 35% and 44% increase for short and long coir fibre, respectively.

When dynamic Young's moduli are calculated from the frequencies obtained, short coir/glass fibre samples had a higher value (6.65 +/- 0.56 GPa with a vibrometer only) than both the control samples (5.48 +/- 0.28 GPa with a vibrometer only) and long coir/glass fibre samples (4.32 +/- 0.80 GPa with a vibrometer only) (Fig. 16). This result is consistent with the ones obtained for

short coir fibre addition in previous arrangement (coir added in middle layer); long coir fibre addition in the symmetrical arrangement affected negatively the stiffness of the sample. Increasing the amount of natural fibre added or control on the orientation could modify this effect.

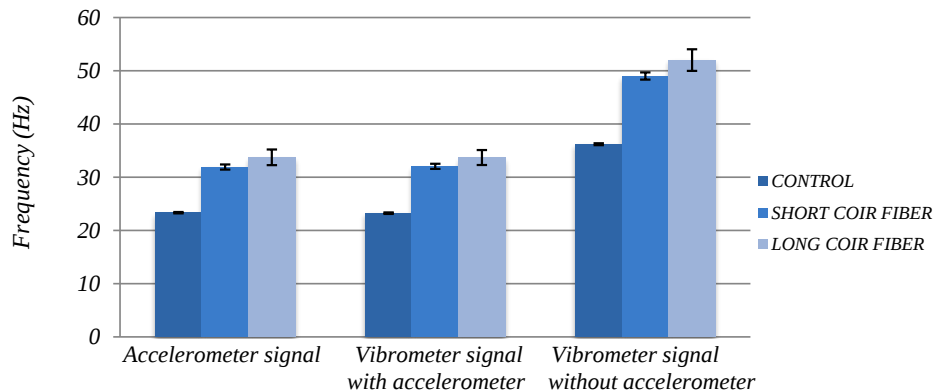


Fig. (15). Vibration frequencies (Hz) of double-layered coir/glass fibres hybrid reinforced extra epoxy composite obtained with the use of an accelerometer and/or a vibrometer.

Damping rate was also investigated with and without accelerometer showing that only vibrometer measurements without accelerometer allowed discriminating among the results. Damping rate of samples made of short coir fibres increased 26% to a value of 0.00613 in comparison to the extra epoxy double-layered control glass fibre composite with damping rate of 0.00487 and samples made of long coir fibre increased 57% to a value of 0.00766 in comparison to the same control (Fig. 17).

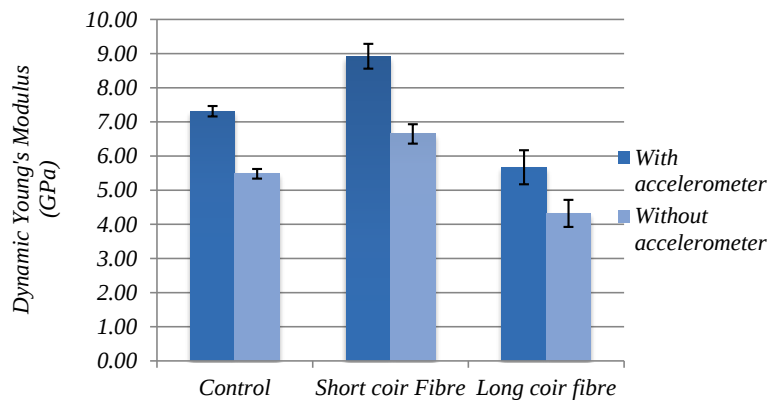


Fig. (16). Dynamic Young's moduli (GPa) of double-layered coir/glass fibres hybrid reinforced extra epoxy composite obtained with the use of an accelerometer and/or a vibrometer.

Damping rate measurement results suggest that coir facilitates energy absorption in coir/glass hybrid composite arrangements in direct proportion to fibres length.

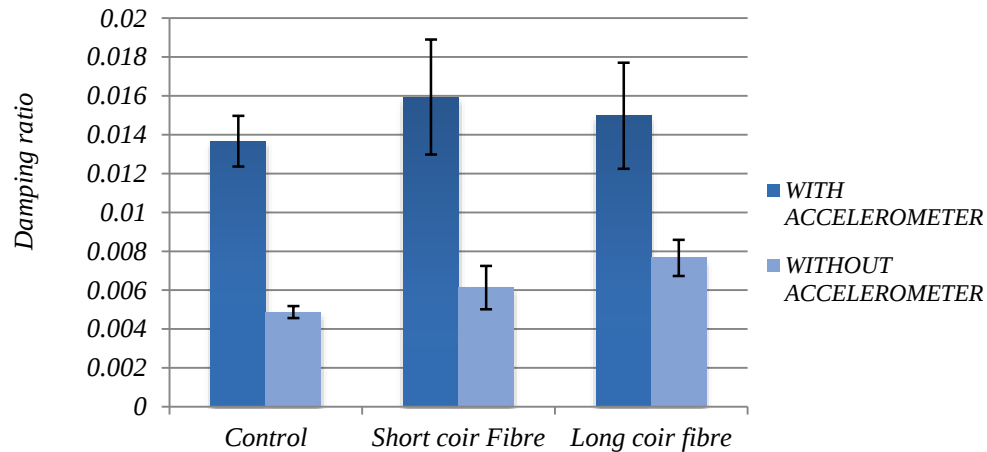


Fig. (17). Damping ratio (Hz) of double-layered coir/glass fibres hybrid reinforced extra epoxy composite obtained with the use of an accelerometer and/or a vibrometer.

Tensile property was also investigated for double-layered coir/glass fibers hybrid reinforced extra epoxy composite and results were consistent with coir middle layered arrangement ones. Quasi-static Young's moduli decreased proportionally to coir fiber size, giving a value of 7.84 $\pm$ 0.16 GPa for the control, 6.96 $\pm$ 0.41 GPa for short coir samples and 5.47 $\pm$ 0.47 for long coir samples (Fig. 18a).

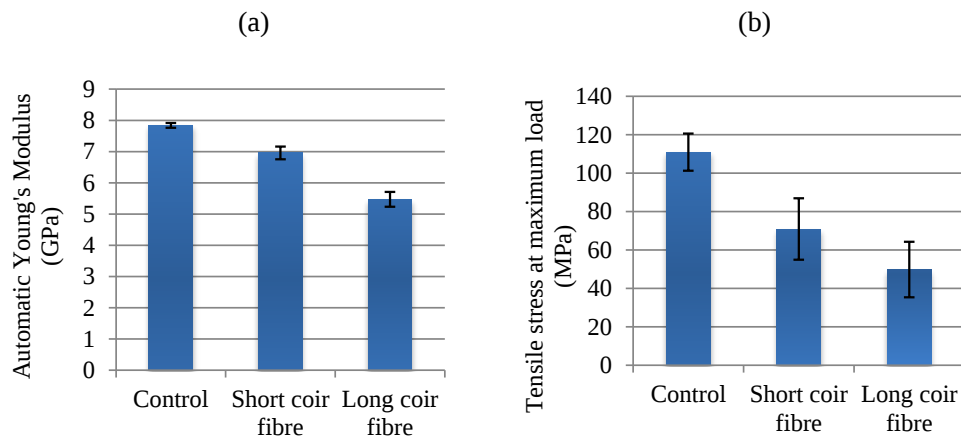


Fig. (18). (a) Quasi-static Young's moduli (GPa) and (b) Tensile stress at maximum load (MPa) of double-layered coir/glass fibres hybrid reinforced extra epoxy composite obtained.

Quasi-static tensile strength was also compared and decreased proportionally to the length of coir fiber used in symmetrical double-layered hybrid reinforced extra composite (Fig. **18b**). Hence, glass fiber extra epoxy composite tensile stress (110.95 +/- 19.39 MPa) was reduced by addition of short coir fiber (70.94 +/- 31.98 MPa) or long coir fiber (49.83 +/- 28.89 MPa).

CONCLUSION

The glass fiber test bed for coir fiber incorporation allowed documenting coir treatment on coir/epoxy adhesion and coir length effect on mechanical properties of the composite material. The comparative study of dynamic and quasi-static properties of plain weave glass/coir fiber reinforced hybrid epoxy composites showed that the samples with a single middle layer coir fiber had an increase in the dynamic elastic modulus value by as much as 150 to 171% with regard to that one of glass fiber samples without coir fiber. Treatment of coir fiber had no statistically significant effect on materials properties or on coir/epoxy adhesion. Higher volumes of epoxy improved coir fiber adhesion and prevented delamination although this condition lowered the dynamic elastic moduli of glass epoxy composite control. Tensile test confirmed that 30% epoxy addition increased stiffness of glass/coir lowering their dynamic and quasi-static Young's modulus. The presence of delamination, in coir/glass fiber hybrids with higher dynamic young's modulus is consistent with the function of the middle layer as a shear stress absorber and low fiber/matrix adhesion.

A different stacking sequence of coir and glass laminates with two symmetrical coir layers' arrangement had a different effect on dynamic Young's modulus and on damping property depending on the length of reinforcement coir fiber used. Long coir/glass fiber reinforced epoxy composite samples exhibited the lowest dynamic and quasi-static elasticity moduli but the highest damping rate. The study suggests that addition of coir fiber layers in composite laminar arrangements must significantly improve fatigue life and acoustic properties due to improved damping properties.

Cantilever configuration experiment resulted in an easy, sensitive and non-destructive test to characterize natural fibers hybrid composite dynamic properties. Comparison of damping rate measurements made with accelerometer and vibrometer allowed demonstrating that only the later has the precision required to discriminate between effects of thin samples configurations. The further modal analysis could be used to compare the precision of the cantilever set up in natural frequency measurement. More studies should be oriented towards coir fiber epoxy composite durability and environmental resistance.

CONSENT FOR PUBLICATION

Not applicable.

CONFLICT OF INTEREST

The authors confirm that this chapter contents have no conflict of interest.

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Declared none.

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Ulisses Targino Bezerra

Ulisses Targino Bezerra has a Doctorate degree in well cementing from the Federal University of Rio Grande do Norte (Brazil). Following a post-doctorate at the University of Minho (Portugal), with the use of chitosan in cementitious materials. He currently works as a Professor and Researcher at the Federal Institute of Education, Science and Technology of Paraíba (Brazil). His research interests include sustainability, steel structure, biomimetics, biomimicry, bio-inspired design. He is a Civil Engineer who dedicated himself to the last decade of this professional career to the observation of the nature and its wonderful mechanisms.